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VOL. 37 No. 333 SEPTEMBER 1951

A SYMPOSIUM ON COMBUSTION REACTIONS IN RELATION TO GAS TURBINE PRACTICE

AN Ordinary General Meeting of the Institute of Petroleum was held at Manson House, 26 Portland Place, London, W.1, on May 19, 1951. The chair was taken by Professor F. H. Garner, O.B.E., Past-President.

Minutes of the Ordinary General Meeting held on April 11, 1951, were read, confirmed, and signed.

The Editor (George Sell) announced the names of members elected since the previous meeting of the Institute.

The following papers were then presented :

FUELS FOR AVIATION AND INDUSTRIAL GAS TURBINES

By M. O. SCOTT,* R. STANSFIELD * (Fellow), and T. TAIT * (Fellow)

INTRODUCTION

THE purpose of this paper is to outline the relationship between production and fuel specifications for aviation turbine fuels; to sketch briefly the range of hydrocarbon fuel properties available and to give the results of tests with fuels of extreme hydrocarbon composition; to outline the combustion problems for residual fuels, and, in so doing, to indicate the direction in which designs rather than fuels must develop if the industrial turbine is to succeed on a large scale.

PART I—AVIATION TURBINE FUELS

FUEL SPECIFICATIONS

Aviation turbine fuel for British aircraft conforms to the Ministry of Supply specification D.E.R.D. 2482 (Table I), and is used for both military and civil aircraft. This is a kerosine-type fuel of boiling range *ca* 150° to 300° C.

The American Specification MIL-F-5616 is similar as far as boiling range is concerned, but, in order to increase available supplies of turbine fuel, their further specification MIL-F-5624 (Table II) is for a "long-cut" material with a much wider boiling range of *ca* 70° to 320° C.

PRODUCTION LIMITATIONS

The gas turbine can burn successfully a wide variety of fuels. The main clauses in the specifications impose limits to the range of physical properties

* Anglo-Iranian Oil Co. Ltd., Sunbury Research Station.

TABLE I

British Specification for Aero Turbine Fuel

Specification :	D.Eng.R.D. 2482 Aviation turbine fuel	
Reference :	M.A.P. Spec. Issue No. 1, 1.4.47 *†	
Test	**Method of test**	**Specification**
Specific gravity 60/60° F	A.S.T.M. D287-39	The sp. gr. shall not be limited but shall be determined and noted.
Distillation :		
20%, ° C	I.P. 28/42	200·0 max
F.B.P., ° C	—	300·0 max
Total distillate, %	—	96·5 min
Residue, %	—	2·0 max
Loss, %	—	1·5 max
Recovery at 200° C, %	—	20·0 min
Colour Lovibond 18 inch cell	I.P. 17/45	4·0 Y
Flash point, ° F	I.P. 33/44	100·0 min
Total sulphur, % wt	A.S.T.M. D90-41T	0·20 max
Corrosion copper strip	I.P. 64/46 (B)	Slight discol. max
Residue on evaporation, mg/100 ml	I.P. 97/46 (T)	6·0 max
Cold test, ° C	I.P. 16/44 (T)	−40·0 max
Aromatics, % vol	I.P. 3/42	20·0 max
Viscosity at 0° F, cs	I.P. 71/45 (T)	6·0 max
Cal. val. net, B.Th.U/lb	D.Eng.R.D. 2478	18,300·0 min
Water tolerance, ml	D.Eng.R.D. 2478	2·0 max
Special requirements	—	Wholly hydrocarbon. Clear and free from suspended dirt and water.
Total acidity	I.P. 1/46 Method B	Shall not exceed 0·10 mg KOH per one g fuel.

* Amended by A.L. No. 1, dated 1.11.48. † Amended by A.L. No. 2, dated 1.4.50.

TABLE II

American Specification for Aero Turbine Fuel

Specification :	MIL-F-5624, 30.3.49	
Test	**Method of test**	**Specification**
Specific gravity, 60/60° F	A.S.T.M. D287-39	0·7275–0·8017
Distillation :		
I.B.P., ° C	A.S.T.M. D86-46	—
90%, ° C	—	204·4 min
F.B.P., ° C	—	315·5 max
Total distillate, %	—	97·0 min
Residue, %	—	1·5 max
Loss, %	—	1·5 max
Total sulphur, % wt.	A.S.T.M. D90-47T	0·5 max
Corrosion copper strip	—	Sl. discol. max
Residue on evaporation, mg/100 ml	A.S.T.M. D381-46 (M)	10·0 max
Accelerated gum—16 hr, mg/100 ml	A.S.T.M. D873-46T (M)	20·0 max
Vapour pressure, p.s.i.	A.S.T.M. D323-45	5·0–7·0
Bromine No.	A.S.T.M. D875-46T (M)	30·0 max
Freezing point, ° C	—	−60·0 max
Aromatics, % vol	A.S.T.M. D875-46T	25·0 max
Water tolerance, ml	—	1·0 max
Heat of combustion (net value) B.Th.U/lb	A.S.T.M. D240-39	18,400·0 min
Inhibitor concentration, lb/5000 U.S.G.	—	1·0 max

of these fuels due to the extreme range of atmospheric conditions under which the aircraft engine has to operate; they have little to do with the combustion process.

These limits in their turn impose restrictions on the availability of fuels from conventional refinery operation, and it may, therefore, be pertinent to refer briefly to the two important factors of freezing point and vapour pressure, which together tend to squeeze aviation gas-turbine fuels into a relatively narrow boiling range.

1. *Freezing Point*

A fundamental requirement is that the fuel will flow freely to the engine under all conditions experienced in flight and, as very low temperatures can be met, the specifications demand low freezing points. The atmospheric temperature may fall as low as −95° C, but for a variety of reasons it is not necessary to specify a fuel freezing point as low as this.

In all crude oils the higher-boiling fractions have freezing points higher than the low-boiling fractions, and this demand for low freezing point tends to restrict the final boiling point and hence the availability of the fuel. This is shown by the following figures which apply to a Middle East crude oil:

Fuel	Freezing point, °C	Yield of crude, % wt
Kerosine type . . .	−40	25
	−60	10
Long-cut type . . .	−40	50
	−60	35

2. *Vapour Pressure*

The disadvantages arising from high vapour pressure are vapour locking in the fuel system and loss of fuel through evaporation or boiling at altitude.

Modern aircraft have very high rates of climb, and the temperature of the fuel in the tanks may be substantially the same during the climb as at ground level. For example, a fuel of 7 p.s.i. Reid vapour pressure will boil at 35,000 ft if at a temperature of 70° F, and the loss of fuel may amount to 10 per cent. Further losses may also result from " slugging " of the fuel in vent pipes.

On the other hand, an increase in the vapour pressure allows increases in available yield, and a valuable gain in fuel quantity can be made if some method is devised for avoiding vapour loss from fuel tanks.

3. *Fire Risk*

The question of fire risk is also associated with vapour pressure and volatility of the fuel, but it will not be discussed here.

Hydrocarbon Fuel Properties

For the purposes of discussion the assumption may be made that fuels boiling in the range 65° to 320° C are being dealt with, and on this basis some of the physical and chemical properties which effect combustion will be examined.

1. *Calorific Value*

The primary aim of the combustion system is to provide the maximum amount of heat with the minimum of fuel flow; the latter may be on a volume or weight basis, depending on the design and duty of the aircraft. The calorific values of various hydrocarbon materials and two specification fuels are shown in Table III.

TABLE III

Fuel type *	Sp. gr., 60/60° F	Boiling range, ° C	Aromatics, % wt	Naphthenes, % wt	Paraffins, % wt	Cal. val. (net)	
						C.H.U/lb	C.H.U/I.G.
Paraffinic material .	0·7475	159–265	2·6	5·2	92·2	10,360	77,400
Naphthenic material .	0·7910	160–270	1·4	51·9	46·7	10,300	81,500
Reference kerosine (RT.2978) . .	0·7940	155–270	19·4	39·2	41·4	10,260	81,500
Long cut (MIL-F-5624)	0·8015	41–286	26·0	—	—	10,100	81,000
Aromatic material .	0·8645	166–253	75·2	11·4	13·4	9,860	85,400

* Full inspection data is given in Table VI. See note on page 497.

A high heat of combustion per unit weight is a characteristic of the paraffinic hydrocarbons and per unit volume, of the aromatic hydrocarbons. The difference in net calorific value per gallon of a highly aromatic material and the paraffinic material shown in the above table is of the order of 10 per cent.

2. *Carbon/Hydrogen Ratio*

The carbon/hydrogen ratio of a fuel is closely linked with calorific value and this is shown in Fig. 1, which has been compiled from experimental results obtained from a number of pure hydrocarbons and actual aviation turbine fuels.[1] For different types of aviation turbine fuels the carbon/hydrogen ratio will range from 5·7 to 6·7 and the gross calorific value from 19,500 to 20,500 B.Th.U/lb (10,100 to 10,500 C.H.U/lb net).

3. *Viscosity*

Viscosity data for individual hydrocarbons are sparse, and a full comparison in relation to hydrocarbon type is impossible. In general, the main hydrocarbon classes have similar viscosities at 20° C, which increase steadily from *ca* 0·5 to 5·0 centipoises throughout the boiling range 100° to 300° C.

The rate of increase in viscosity is more pronounced above 240° C boiling point, at which the mean value is 2·0 centipoises. The viscosity limit of the present British specification is 6 centistokes (maximum) at 0° F, which is equivalent to *ca* 5 cp with a fuel of sp. gr. 0·8055. No limitation is imposed in the American specification, but the viscosity of a long cut would probably not exceed 2 centistokes at 0° F (*ca* 1·6 cp with a fuel of sp. gr. 0·8015). Viscosity characteristics at lower temperatures down to −60° C are not available, but may assume importance in view of the temperatures that may be encountered at high altitude.

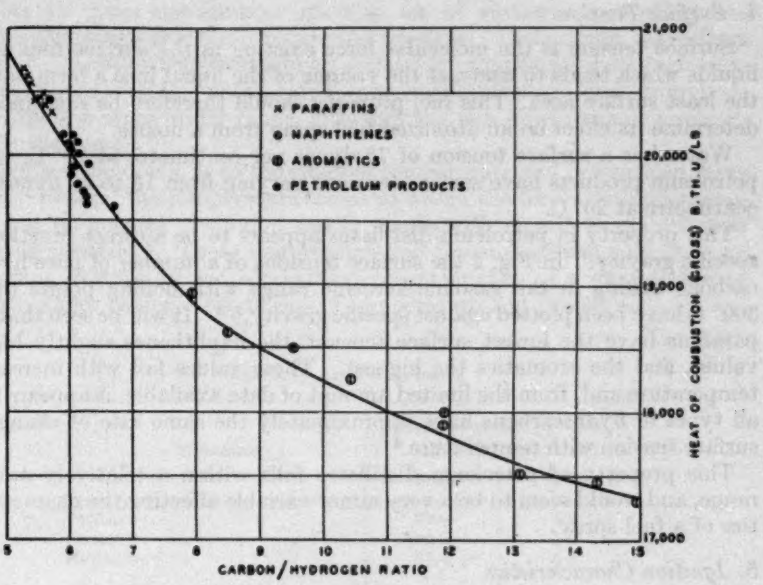

FIG. 1

HEAT OF COMBUSTION V. CARBON/HYDROGEN RATIO

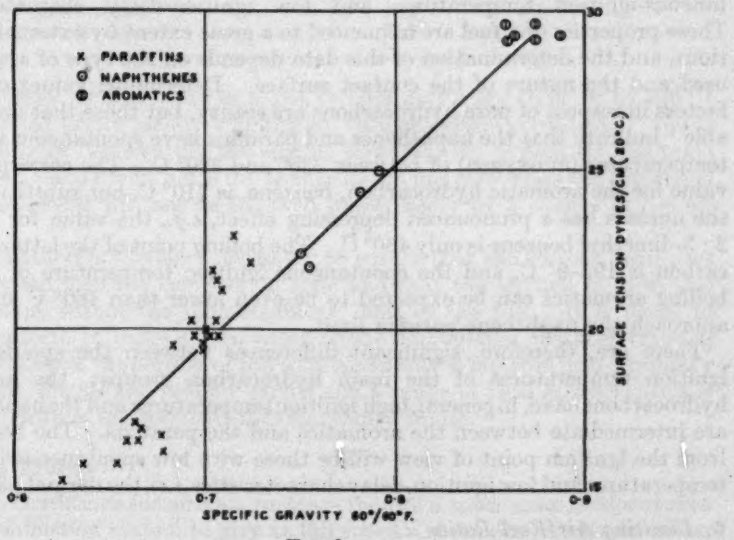

FIG. 2

VARIATION OF SURFACE TENSION WITH SPECIFIC GRAVITY

4. *Surface Tension*

Surface tension is the molecular force existing in the surface film of all liquids which tends to contract the volume of the liquid into a form having the least surface area. This fuel property should therefore be examined to determine its effect on an atomized fuel spray from a nozzle.

Water has a surface tension of 76 dynes per centimetre at 20° C, while petroleum products have surface tensions varying from 15 to 40 dynes per centimetre at 20° C.

This property in petroleum distillates appears to be a direct function of specific gravity. In Fig. 2 the surface tensions of a number of pure hydrocarbons boiling in the gasoline/kerosine range with boiling points up to 300° C have been plotted against specific gravity.[2, 3] It will be seen that the paraffins have the lowest surface tension, the naphthenes slightly higher values, and the aromatics the highest. These values fall with increasing temperature and, from the limited amount of data available, it appears that all types of hydrocarbons have approximately the same rate of change of surface tension with temperature.[4]

This property of petroleum distillates falls within a relatively narrow range, and would seem to be a very minor variable affecting the characteristics of a fuel spray.

5. *Ignition Characteristics*

Since the heat released per unit volume of a gas-turbine combustion chamber is very high and the length of combustion zone limited, it follows that the flame zone must be as close as possible to the fuel-injector nozzle. In general, therefore, the fuels of best performance will require low spontaneous-ignition temperatures and low ignition-delay characteristics. These properties of a fuel are influenced to a great extent by external conditions, and the determination of this data depends on the type of apparatus used and the nature of the contact surface. Determined values of these factors in respect of pure hydrocarbons are scanty, but those that are available [1] indicate that the naphthenes and paraffins have spontaneous ignition temperatures (in oxygen) of between 230° and 320° C. The corresponding value for the aromatic hydrocarbon, benzene, is 710° C, but substitution in the nucleus has a pronounced depressing effect, *e.g.*, the value for 1-ethyl 2 : 3-dimethyl benzene is only 460° C. The boiling point of the latter hydrocarbon is 193–9° C, and the spontaneous ignition temperature of higher-boiling aromatics can be expected to be even lower than 460° C and may approach the naphthene/paraffin limit.

There are, therefore, significant differences between the spontaneous-ignition temperatures of the main hydrocarbon groups; the aromatic hydrocarbons have, in general, high ignition temperatures and the naphthenes are intermediate between the aromatics and the paraffins. The best fuels from the ignition point of view will be those with low spontaneous-ignition temperatures and low ignition-delay characteristics, *i.e.*, the normal paraffins.

6. *Limiting Air/Fuel Ratios*

There are only small differences in ignition limits for hydrocarbons, the rich limit for fuels in the kerosine range being approximately 5 : 1 air/fuel ratio by weight, while the weak limit is in the region of 25 : 1.

Table IV gives the ignition limits in air of various types of hydrocarbons at ground-level temperature and pressure. These limits, taken from a survey of ignition temperatures by Jones,[5] are similar for most hydrocarbon types, except the unsaturated compounds ethylene and propylene, which show a much wider range, although the rich limit remains approximately the same.

There is some doubt as to the effect of temperature and pressure on these limits. Raising the temperature seems to widen the limits without exception, but no general prediction can be made with regard to the effect of changing pressure.[6] These temperature and pressure effects may have an important bearing on the combustion characteristics of a gas turbine at altitude under extreme conditions of temperature and pressure.

TABLE IV

Limiting Air/Fuel Ratios

Material	Air/fuel ratios (by wt)	
	Weak	Rich
Pentane	27·0	4·9
Hexane	25·5	4·6
Heptane	27·4	4·5
Ethylene	55·0	5·3
Propylene	32·6	5·9
Benzene	25·0	5·2
Toluene	23·5	4·4
*cyclo*Propane	27·2	6·3
*cyclo*Hexane	24·5	3·9

The overall air/fuel ratio in a gas turbine may vary from 50 to 100 : 1 air/fuel ratio under steady running at various engine conditions. When accelerating or decelerating the engine, however, the overall air/fuel ratio will exceed these limits, since the change in the fuel flow when the throttle is opened or closed will not be followed immediately by a change in the air flow.

Some method is therefore necessary to ensure that the correct quantities of air are led into the combustion zone and that the air/fuel ratio in this zone is kept within the inflammability limit of the fuel. It is usual to arrange a form of baffle at the entry to the combustion chamber through which a constant proportion of the total air supply is metered into a primary zone where the air and fuel are mixed and a range of local air/fuel ratios is produced within the required inflammability limits.

7. *Flame Velocity*

Design conditions for aircraft turbines require a total cross-sectional area of the combustion system to give at full speed a mean air velocity based on the total air-mass flow and compressor-delivery density of 100 to 300 ft/sec.

For hydrocarbon fuels, combustion velocities are very low, and range from 1 to 2 ft/sec under laminar-flow conditions.

These low flame velocities make it impossible to stabilize the flame by establishing an equilibrium between the gas velocity and the flame speed. and alternative means for keeping the flame alight must be sought.

Again, some form of baffle is usually employed to create turbulence and swirl in the primary zone to stabilize the flame and provide mixing for combustion purposes. The type of baffle usually employed uses swirl and peripheral air admission to the primary combustion zone, and causes part of the freshly burning gases to re-circulate in the primary zone. This reverse flow on the centre line of the combustion chamber is found to have a very powerful stabilizing effect, anchoring the flame near the burner despite the high mean velocity of the gases in the down-stream direction.

The problem is, however, to provide adequate mixing and flame stabilization with the minimum of pressure loss. Most combustion chambers achieve good mixing and stability with a pressure loss of not more than 5 per cent.

8. *Flame Temperatures*

The maximum temperature of the combustion products at present considered acceptable by the materials of the turbine is 800° to 850° C. At sea-level under full-load conditions the temperature of the air entering the combustion chamber may be raised 200° C, by passage through the compressor. The maximum temperature rise that may be tolerated, therefore, by combustion of the fuel is some 600° to 650° C.

Very few data are available on flame temperatures of individual hydrocarbons, but the maximum flame temperature for hydrocarbon fuels may be taken as approximately 2000° C. This maximum temperature will occur at a mixture strength slightly richer than the theoretical, owing to dissociation of the molecular products of combustion. At pressures above ground-level atmospheric this temperature rises slightly.

Although flame temperatures of 2000° C may be obtained locally, some excess air is usually present in the primary zone which will reduce the general flame temperature to approximately 1500° C. Even at this temperature cooling air must be added to the products of combustion to avoid overheating the turbine blading. The method of introducing this excess air is of the utmost importance if combustion loss due to flame chilling is to be avoided.

9. *Limits of Properties*

It is evident that fuels suitable for aircraft gas turbines may contain an almost unlimited number of constituents with properties that lie between tolerably well-defined limits.

These limits, for those hydrocarbons in the boiling range 65° to 300° C on which information is available,[1] are summarized in Table V.

Thus, for example, the paraffins are responsible for the lowest densities, viscosities, latent heats, carbon contents, and calorific value (per unit volume). The paraffin hydrocarbons of straight-chain structure also have high freezing points and low spontaneous-ignition temperatures and ignition delay times.

It follows from the manner in which these various properties are interrelated that while some combinations of properties are possible in the same

fuel, others are not, and, although blending of fuels of substantially different compositions can be resorted to in order to produce mixtures of intermediate characteristics, it is not possible, on the basis of existing knowledge, to escape from the following generalizations concerning straight-run petroleum distillates :—

(*a*) The highest ignition quality in terms of the lowest spontaneous-ignition temperatures and lowest ignition-delay times is not associated with—

(i) the highest density;
(ii) the lowest freezing point; or
(iii) the highest calorific value by volume.

(*b*) For the lowest possible freezing point, hydrocarbons of the most favourable ignition and combustion characteristics, *i.e.*, the normal paraffins, must give way to those of less favourable combustion properties, *i.e.*, the branched-chain paraffins, the substituted *cyclo*pentanes and *cyclo*hexanes, and the substituted monocyclic aromatics.

TABLE V

Limits of Properties of Hydrocarbons, B.P. 65° to 300° C

Property	Lower limit			Upper limit		
	At b.p. 65° C	At b.p. 300° C	At mean b.p.	At b.p. 65° C	At b.p. 300° C	At mean b.p.
Density at 20° C, g/ml .	0·66	0·77	0·74	0·88	0·89	0·88
Visc at 20° C, cp . .	0·3	4·0	1·0	1·0	6·0	1·5
Specific heat . . .	0·41	0·37	0·40	0·54	0·50	0·53
Lat. heat vap., cal/g .	75·0	40·0	60·0	100·0	52·0	75·0
Carbon content, % wt .	83·7	85·0	84·5	92·3	88·1	89·5
Hydrogen content, % wt.	7·7	11·9	10·5	16·3	15·0	15·5
Heat of comb. (gross), B.Th.U/lb . . .	18,090	19,350	18,540	20,970	20,340	20,520
Heat of comb. (gross) B.Th.U/I.G . .	138,400	156,620	151,850	159,190	172,220	163,150
Surface tension, dynes/cm	18·0	28·0	23·0	28·0	32·0	30·0

The effect of changes in ambient conditions of temperature and pressure on the properties of hydrocarbons, in particular at low temperatures and pressure, has received little attention. For example, there is no simple relationship between pressure and minimum ignition temperatures for individual hydrocarbons or even for the main groups of hydrocarbons.

THE COMBUSTION PROCESS

The mechanism of the reactions by which hydrocarbon combustion takes place has been intensively studied for a long time, but there is still a lot to be learned; the problem is not made easier by the high combustion intensities and the wide range of temperatures and pressures under which combustion must proceed in aircraft gas turbines.

The work carried out on reciprocating engines has already shown the importance of chemical characteristics of fuels, but if gas turbine behaviour

is also strongly influenced by chemical factors, the elucidation of these effects will be a matter of considerable difficulty.

Extensive testing of a wide variety of fuels for aviation gas turbines is in progress on complete engines, single-combustion-chamber test rigs, and by laboratory-scale research. Elaborate equipment and large quantities of fuel are required for making complete tests on full-scale engines and for that reason initial testing of new fuels is carried out on single-combustion-chamber test rigs.

Fuel Testing

Engine tests must, of course, provide the final criterion of whether the chamber or fuel is satisfactory, but the majority of tests can be better carried out on single-combustion-chamber test rigs running at simulated ground or flight conditions. These tests are normally made in standard aircraft gas-turbine combustion chambers, and the following combustion characteristics, which are influenced by the fuel, are examined :—

1. Fuel economy and combustion efficiency.
2. Stable burning range.
3. Combustion chamber and burner deposits.
4. Exhaust gas temperature distribution.

1. *Fuel Economy and Combustion Efficiency*

The combustion efficiency of a fuel varies with engine-operating conditions and, for a present-day standard type of aircraft combustion chamber, at least 98 per cent efficiency is achieved for a wide range of fuels with high engine speeds at ground level or low altitude.

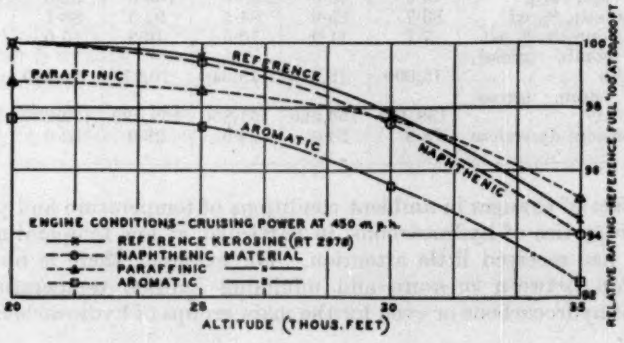

Fig. 3

Relative combustion efficiency v. altitude

Combustion efficiency, however, decreases with a reduction in engine speed and also with reduced fuel and air flows, such as occur at high altitude. This point is illustrated in Fig. 3, which refers to tests made at Sunbury, in which the relative efficiency of three fuels of varying chemical type have been compared with a reference aviation kerosine in a combustion chamber. These three fuels consisted of " aromatic," " naphthenic," and " paraffinic "

materials of kerosine boiling range, and their full inspection data is given in Table VI.*

TABLE VI

Inspection Data

Test	Method of test	Reference kerosine (RT. 2978)	Naphthenic material	Paraffinic material	Aromatic material
Sp. gr. at 60/60° F	I.P. 59/49	0·7940	0·7910	0·7475	0·8645
Distillation Test:					
I.B.P., °C	A.S.T.M. D86-46	155·5	160·0	159·0	166·0
2% recovered at, °C	—	164·0	171·0	166·0	174·0
5% recovered at, °C	—	170·0	175·0	170·0	176·5
10% recovered at, °C	—	177·5	184·0	173·5	179·0
20% recovered at, °C	—	187·0	191·5	180·0	184·5
30% recovered at, °C	—	196·5	198·0	188·0	189·0
40% recovered at, °C	—	205·0	204·0	195·0	194·0
50% recovered at, °C	—	211·5	210·0	201·0	199·0
60% recovered at, °C	—	218·5	215·5	207·5	205·5
70% recovered at, °C	—	227·0	222·5	215·0	212·0
80% recovered at, °C	—	236·0	232·0	226·0	220·5
90% recovered at, °C	—	249·0	245·5	241·5	231·5
F.B.P., °C	—	271·0	270·5	265·0	253·0
Total distillate, %	—	98·0	98·0	99·0	98·5
Residue, %	—	1·5	1·5	1·0	1·0
Loss, %	—	0·5	0·5	0·0	0·5
Recovered at 185° C, %	—	17·0	11·0	26·0	21·5
Recovered at 200° C, %	—	34·0	33·5	48·5	51·0
Recovered at 240° C, %	—	83·5	86·0	89·5	94·0
Colour Lovibond (in cell)	I.P. 17/45	0·3Y + 0·1R	2·0Y + 0·4R	0·6Y + 0·2R	3·1Y + 0·1R
Colour Saybolt	A.S.T.M. D156-49	—	+26·0	+30·0	—
Flash point, °F	I.P. 33/44 or 34/47	155	120·0	117·0	121·0
Total sulphur, % wt	I.P. 107/49	0·037	0·021	0·003	0·238
Corrosion test (cu strip)	I.P. 64/46 (B)	sl. disc.	black	peacock	brown
Doctor test	I.P. 30/44	negative	negative	negative	negative
Residue on evap., mg/100 ml	I.P. 97/46 (T)	5·0	2·0	trace	2·0
Bromine No.	A.I.O.C. 117/40	1·0	1·0	1·0	1·0
Cold test	I.P. 16/44 (T)	−42·0	−43·0	−30·0	−60·0
Aniline point (1), °C	I.P. 2/47	65·9	73·2	80·7	40·7
Aniline point (2), °C	I.P. 2/47	76·7	75·9	82·9	63·9
Viscosity at 100° F, cs	I.P. 71/47 (T)	1·54	1·53	1·30	1·16
Viscosity at 0° F, cs	I.P. 71/47 (T)	4·29	4·58	3·97	3·34
Cal. val. (gross), B.Th.U/lb	I.P. 12/45 (Mod.)	19,776	19,973	20,193	18,930
Water tolerance	A.I.O.C. 232/44	passes	passes	passes	passes
Carbon, % wt	—	85·8	85·5	84·5	88·7
Hydrogen, % wt	—	14·2	14·5	15·1	10·2
C/H ratio	—	6·04	5·9	5·6	8·7
Acidity, mg KOH/g	I.P. 1/46 (B)	—	nil	nil	nil
Hydrocarbon Type Analysis:					
Aromatics, % wt	—	19·4	1·4	2·6	75·2
Naphthenes, % wt	—	39·2	51·9	5·2	11·4
Paraffins, % wt	—	41·4	46·7	92·2	13·4

It will be noted that the aromatic material gave the lowest efficiency over the range of altitudes available for the test, and that the efficiency of the paraffinic fuel decreased less with increasing altitude than any of the others.

It has already been shown that the paraffin hydrocarbons, in particular the normal paraffins, have superior ignition and combustion characteristics, and further tests with these three fuels have shown that the paraffinic material gave better combustion efficiencies at weaker air/fuel ratios than either the reference fuel or the other two fuels (Fig. 4).

This is an important feature from the point of view of fuel economy; it will be noted that similar peak-efficiency levels may be obtained for all these kerosines, although the fuel giving maximum efficiency at the weakest air/fuel ratio appears to give the highest fuel economy. However, the calorific value of the fuel must be taken into account, and the heat released on a volume and a weight basis compared with the reference fuel has been

* These fuels were specially prepared for experimental purposes and are not commercially available.

plotted in Figs. 5 and 6. It will be seen that, for the given altitude range, the aromatic material gave the highest heat-release rates per unit volume, and the paraffinic kerosine the highest values on a weight basis.

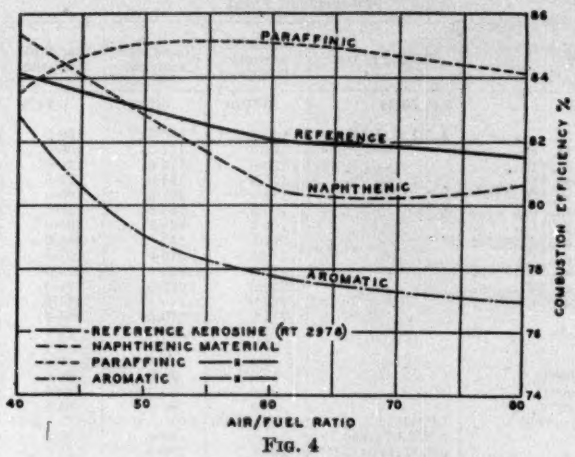

FIG. 4

COMBUSTION EFFICIENCY V. AIR/FUEL RATIO

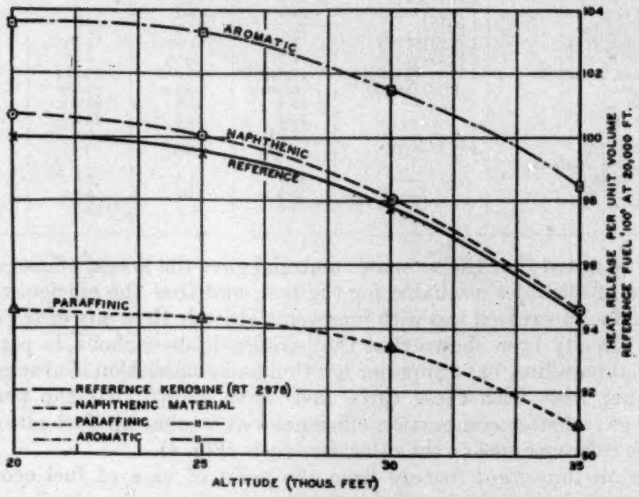

FIG. 5

RELATIVE FUEL ECONOMY ON A VOLUME BASIS V. ALTITUDE

It should be emphasized that the foregoing remarks relate to special fuels with wide differences in hydrocarbon composition and that the normal variations between production fuels are unlikely to affect engine performance significantly.

The more volatile less viscous fuels also tend to give higher efficiencies under adverse engine-operating conditions, *i.e.*, high altitude and low engine speeds. However, by selecting suitable air/fuel ratios, a wide range of fuel types may be made to give similar efficiencies, although only by making modifications to the combustion chamber to suit particular fuels.

With a given combustion chamber, differences in efficiency may result with different fuels, but a more important criterion is the heat released for unit quantity of fuel. Results of combustion-rig tests, using a standard

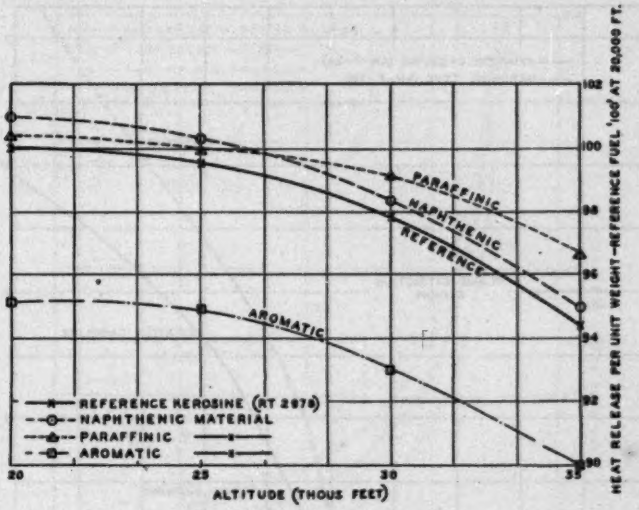

FIG. 6

RELATIVE FUEL ECONOMY ON A WEIGHT BASIS V. ALTITUDE

aircraft combustion chamber at simulated high-altitude-flight cruising conditions to compare the heat-release rates of various fuel types, are given in Table VII.

TABLE VII

Fuel	Boiling range, °C	Combustion efficiency, %	Heat released (net)	
			C.H.U/lb	C.H.U/I.G.
Aviation gasoline (100/130 Grade)	53–174	85	8,900	66,000
Long cut (MIL-F-5624)	60–249	83·5	8,700	66,400
Kerosine (D.E.R.D. 2482)	148–264	83	8,500	67,600

At these conditions the aviation reference kerosine gave approximately 3 per cent better fuel economy on a volume basis than the aviation gasoline, although on a weight basis the gasoline was superior by 4½ per cent.

For maximum economy at high altitude a long cut or gasoline containing a high proportion of paraffins is desirable. For low or medium altitude flight the most suitable fuel will depend on the type of aircraft and whether

fuel supplies are limited by weight or volume considerations : if by weight a gasoline or long cut containing a high proportion of paraffins is desirable, if by volume an aromatic kerosine.

2. *Stable Burning Range*

In flight at high altitude a ceiling is reached above which the combustion chamber fails to provide exhaust gas at a sufficiently high temperature for the turbine at the operating condition of the engine.

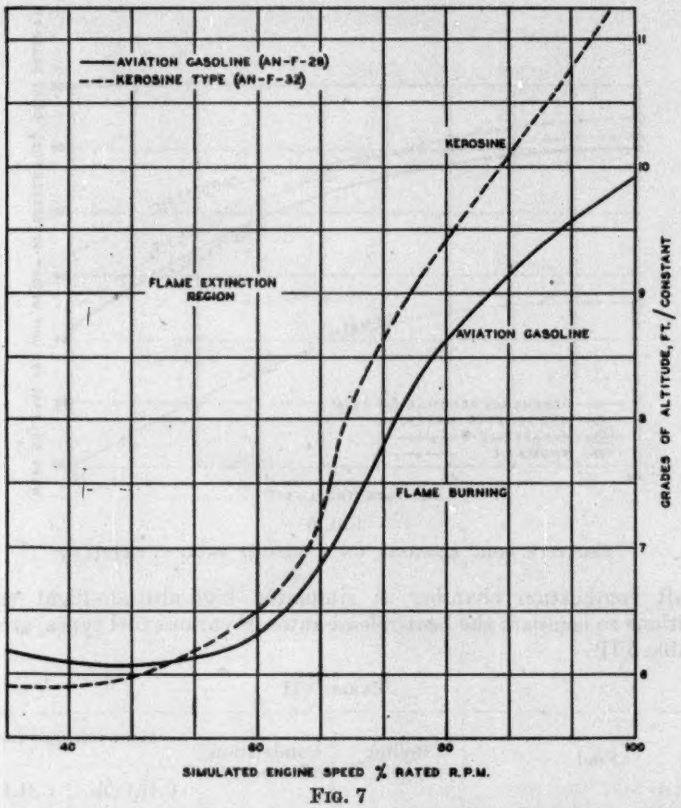

FIG. 7

ALTITUDE OPERATIONAL LIMITS FOR AVIATION GASOLINE AND A KEROSINE FUEL TYPE

Gibbons and Jonash [7] have compared the altitude operational limits of a kerosine and a gasoline. The results obtained (Fig. 7) for the two fuels show that at low engine speeds the altitude limits were practically the same, but, at high simulated engine speeds, the kerosine gave the higher limit. This fact does not seem consistent with the previous combustion efficiency correlation, but is due to the kerosine, although burning at low efficiency, continuing to give a temperature rise after the gasoline has reached its limit. Eventually, of course, the kerosine also reaches a temperature-rise limit, but at a higher altitude.

The stable burning range of a fuel is affected by other factors, and combustion must proceed smoothly under all conditions of operation, including the transient conditions of deceleration and acceleration.

Combustion extinction, therefore, will occur when either weak- or rich-mixture limits are exceeded, weak limits being reached when the fuel flow and hence the fuel pressure is reduced, thereby adversely affecting atomization and mixing of the air/fuel mixture. Flame extinction due to extreme mixture strengths may be largely controlled by a suitable design of fuel

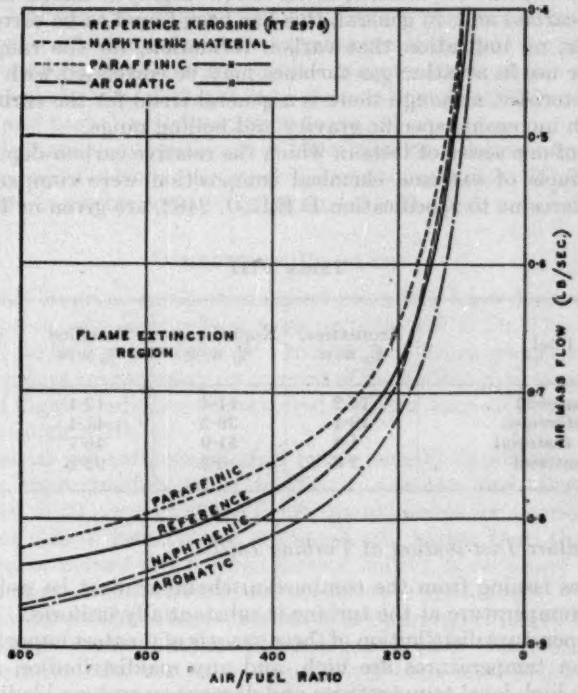

FIG. 8

STABLE BURNING RANGE

system and burners, but limitations of stable burning range will still occur at high altitude.

Tests at Sunbury with paraffinic, naphthenic, and aromatic material of similar boiling range and viscosity showed, as expected, that the paraffins gave much higher weak extinction limits than either of the others, the aromatics giving the lowest limiting air/fuel ratios; comparison with the reference kerosine is shown in Fig. 8.

3. *Combustion-chamber Deposits*

The mechanism of burner and flame tube fouling with deposits of carbonaceous materials is not known, but experience has shown that certain operating conditions are most likely to give rise to this trouble. For example,

at weak-mixture engine-cruising speeds, with comparatively low main-burner pressures carbon, build-up may be heavy.

The presence of carbon on or around the burner tends to upset the spray pattern and leads to lower combustion efficiencies, which in turn lead to greater rates of deposit formation. In addition, the presence of deposits on the flame tubes and an uneven spray pattern lead to local overheating resulting in buckling and ultimate failure of the tubes.

It would be expected that fuels which give relatively low combustion efficiencies, *i.e.*, the less volatile, more viscous highly aromatic fuels, would give more carbon and, in general, this has been found to be correct. There is, however, no indication that carbon formation, for the range of fuels suitable for use in aviation gas turbines may be correlated with any single fuel characteristic, although there is a general trend for the carbon deposit to rise with increasing specific gravity and boiling range.

Results of one series of tests in which the relative carbon-deposit ratings for three fuels of extreme chemical composition were compared with a reference kerosine to specification D.E.R.D. 2482, are given in Table VIII.

TABLE VIII

Fuel	Aromatics, % w/w	Naphthenes, % w/w	Paraffins, % w/w	Relative carbon rating, %
Aromatic material . .	75·2	11·4	13·4	700
Kerosine (reference) . .	19·4	39·2	41·4	100
Naphthenic material .	1·4	51·9	46·7	70
Paraffinic material . .	2·6	5·2	92·2	10

4. *Temperature Distribution at Turbine Inlet*

The gases issuing from the combustion chamber must be well mixed so that their temperature at the turbine is substantially uniform.

The temperature distribution of these gases is of greatest importance when mean outlet temperatures are high, and any maldistribution may cause excessively high local temperatures and damage to turbine blading.

Apart from design faults, lack of uniformity is the result of too long a flame or uneven spray pattern caused by partial blockage of the burner or by deposits in the flame tube. Differences due to fuel composition have so far been found to be only slight, the narrow-cut kerosines being slightly superior to the gasolines and long-cut fuels.

PART II—INDUSTRIAL GAS TURBINE FUELS

FUEL SPECIFICATIONS

The five classes of fuel considered for use in industrial gas turbines are : (*a*) gas, (*b*) distillate oils, (*c*) residual oils, (*d*) coal, (*e*) peat. To these waste heat may be added. This paper deals with only residual fuels for which no general specifications apply in connexion with gas turbine use.

Fuel Properties

The efficiency of the gas turbine is not high, and thus for general industrial purposes it is imperative to operate with the cheapest possible fuel, *i.e.*, residual, which does not have to bear the cost of any expensive processing treatments by the refiner. The future of the industrial gas turbine seems to be dependent on its ability to burn heavy residual fuel oils, unless its capital cost and maintenance is low enough to justify the use of more expensive distillate oils.

With residual fuels the only feature about which there seems to have been much concern is ash content, and the significance of this may be appreciated when it is remembered that a gas turbine using fuel with an ash content of 0·01 per cent at the rate of 20,000 lb/hr passes about 4½ tons of ash through the nozzles and past the blades in 5000 hours.

Deposits left after combustion may affect turbine efficiency and increase maintenance, and for these reasons it is desirable to reduce to a minimum any adventitious matter which may be carried in the fuel.

Combustion Problems

For aircraft engines, small combustion chambers have been developed to burn kerosine, with heat-release rates up to 5×10^6 B.Th.U/cu.ft/hr/atm with overall air/fuel ratios from 5 : 1 to 500 : 1. These particularly stringent requirements are necessary on account of the limited space available and the range of flight conditions encountered between take-off at ground level and idling at high altitude.

For industrial gas turbines, air/fuel ratios usually lie within a narrower range, from approximately 80 : 1 to 200 : 1, and the heat-release rate is reduced to 10 to 20 per cent of the figure quoted above for aircraft engines. This reduced rate of heat release, although still higher than that of conventional steam-boilers and oil-fired marine boilers, is necessary to permit long combustion-chamber life and the use of lower-grade fuels.

The particular problems associated with the burning of heavy fuels have not yet been fully explored in the industrial gas turbine. Various degrees of success have been achieved but it has not yet been established that continuous running with heavy residual fuels under acceptable service conditions can be attained with certainty.

Four particular problems are associated with the fuel; these are :—

(*a*) Atomization of the fuel is difficult due to its high viscosity. The quality of atomization of a heavy fuel when leaving the burner should be superior to that from a distillate fuel, as a greater specific surface area of the spray is required than for successful combustion of kerosine or gas oil. This will tend to give improved evaporation and a reduced combustion period and enable complete combustion of the fuel to be carried out in a primary zone of a reasonable size. If combustion is not complete by the time the secondary air is admitted, flame chilling occurs and poor combustion efficiency results. Improved fuel atomization may be effected by various means, such as combining preheating of the fuel with the use of higher fuel-pump pressures and adjustable spill burners.

(*b*) Low volatility of the fuel tends to prolong the combustion reaction, and the combustion-chamber design must take into account the longer time

required for complete combustion. High temperatures in the primary or reaction zone would be of assistance both in this case and in (*a*) above, but any advantage here must be balanced against reduced flame-tube life and increased carbon formation which may choke the fuel burner or air inlets to the flame tube.

(*c*) Incombustible ashes are present in the exhaust gases, and may cause difficulty with the performance of the turbine and heat exchanger due to build-up of deposits.

(*d*) Various inorganic compounds may be present in the exhaust gases to cause corrosion of parts of the plant with which they come in contact.

The first two problems are mainly questions of design, and should not present any undue difficulty, although combustion-chamber design is still an art rather than a science.

Deposit formation and corrosion are believed to be linked with the design and with the materials used for making the combustion chamber and other equipment, although the engine operator is mainly concerned with their effect on performance and maintenance.

Turbine and Heat-exchanger Deposits

The combustion of residual fuels tends to give deposits of ash on surfaces exposed to the exhaust-gas stream. The work to date at Sunbury on the analysis of these deposits has shown them to consist largely of sodium sulphate and vanadium pentoxide. Sodium vanadates may also be present.

The melting points of these substances, given in Table IX, are of some interest.

Table IX

Substance	Approx melting point	
	°C	°F
Sodium metavanadate . .	630	1166
Sodium pyrovanadate . .	640	1184
Vanadium pentoxide . .	690	1274
Sodium orthovanadate . .	850	1562
Sodium sulphate . . .	880	1616

It will be seen that the vanadium pentoxide is probably in the molten state at the turbine entry under normal operating conditions, and the possibility exists that this molten ash will collect further particles from the gas stream and so build-up deposits.

Inorganic Constituents of Crude Oil

An extensive survey made at Sunbury of various crude and fuel-oil ash constituents has shown that the ash content of the crude oils tested varied between 1 part and 110 parts per 100,000. Almost without exception the samples contained vanadium, and the probable maximum limit of vanadium concentration occurs in a South American crude oil which contains 40 parts of vanadium per 100,000. The sodium contents were generally lower than

the vanadium, the maximum concentration not exceeding 16 parts per 100,000. Iron and nickel were also present in moderate concentrations in the ash, and many other elements were present in small amounts.

In view of the reputed deleterious effect of vanadium in fuels for gas-turbine plant, work was carried out at Sunbury to determine the chemical nature of the vanadium, and, in the crude oils examined, it was found that it was present as a complex vanadium porphyrin which is quite a stable compound. A number of possible ways were also investigated of effecting removal or reduction of vanadium from the same crude oils, but none of the experiments was successful, and it is a matter of some doubt if a simple and economic process can be developed for this purpose. This perhaps is not surprising because it was previously considered quite an achievement to reduce the sulphur content of aviation gasoline for piston engines to 10 parts per 100,000, and, in the case of vanadium in residual fuels, this represents the approximate starting point.

The presence of sodium in residual fuels may also cause trouble by deposit formation, although if the fuel ash contains vanadium the presence of some sodium may be an advantage. The bulk of the sodium present in fuel oil is in the form of oil-insoluble salts consisting mainly of sodium sulphate and the remainder chiefly as sodium chloride. No carbonate or hydroxide has been detected. The presence of naphthenic acids in some crudes may give rise to oil-soluble sodium naphthenates, but there is no evidence that this inherent sodium may form a large proportion of the ash content of a residual fuel.

During small-scale investigations at Sunbury it has been shown that water washing, followed by efficient centrifuging, can remove up to 50 per cent of the sodium present in the fuel oils, and that steaming and centrifuging may remove almost all the sodium content; these methods may be difficult to apply on a cheap commercial scale. It is of interest to note that the vanadium contents of the fuels examined were unaffected by this treatment.

Fuel-ash Deposits

In view of the difficulties of reducing the vanadium and sodium contents of residual fuel, the problem of turbine-blade deposits has been studied at Sunbury on a combustion rig primarily with the object of finding possible methods for inhibiting or rendering these deposits innocuous. The rig was constructed so that the products of combustion were passed over dummy turbine blades under conditions comparable with full-scale operation. The fuel used initially was kerosine with added ash constituents in the form of oil-soluble compounds of vanadium, sodium, calcium, etc. By adding the individual components of a fuel-oil ash to the kerosine, the deposition effects of residual fuels were reproduced. This method had the advantage that it enabled the fuel-ash variables to be studied independently, while the rate of deposition could be accelerated by increasing the concentration of the ash constituents. The following test results are of significance :—

(*a*) Over the range of concentrations tested, vanadium and sodium each gave increased deposit weight with increased concentrations (Figs. 9 and 10).

(*b*) Sodium gave more than twice the weight of deposit obtained from an

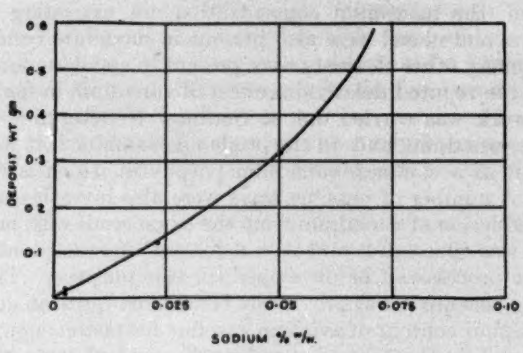

FIG. 9

DEPOSIT WEIGHT PER HOUR FOR VARIOUS SODIUM CONCENTRATIONS

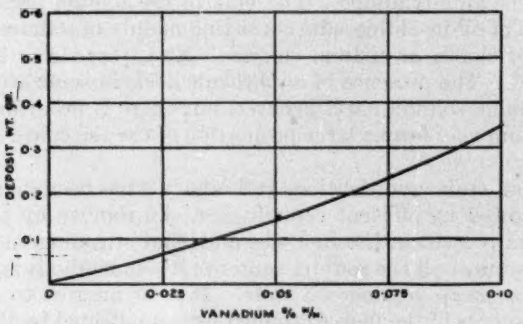

FIG. 10

DEPOSIT WEIGHT PER HOUR FOR VARIOUS VANADIUM CONCENTRATIONS

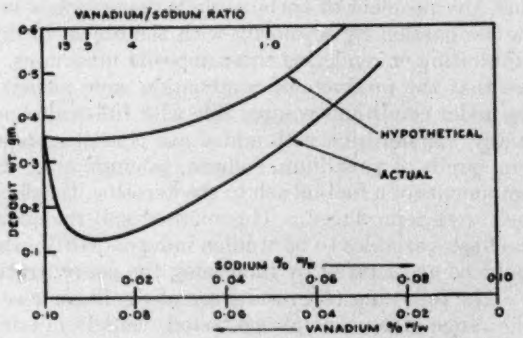

FIG. 11

COMPARISON OF ACTUAL AND HYPOTHETICAL DEPOSITS WITH SODIUM AND VANADIUM COMBINED

equal weight concentration of vanadium. Examination of the deposit from sodium showed it to consist of sodium sulphate which was probably formed in the combustion chamber by the sodium ash and sulphur in the fuel.

(*c*) The extent to which a fuel containing both sodium and vanadium formed deposits depended on—

(i) The total concentration of vanadium and sodium.

(ii) The vanadium/sodium ratio. Under the conditions of test a minimum deposit rate was obtained at ratios in the range 4 : 1 to 12 : 1 (Fig. 11).

The hypothetical curve in Fig. 11 has been constructed from the two curves from Figs. 9 and 10, and indicates the total weight of deposit which is expected from various combined proportions of vanadium and sodium compounds in the fuel ash. The actual results obtained are shown on the second curve (Fig. 11), and a minimum point is seen.

When burning residual fuels, however, such effects may largely be masked by combustion conditions, and it was found, for example, that a trace of carbon in the exhaust-gas stream almost completed inhibited ash deposits. The mechanism of this effect is not known.

Corrosion Problems

Apart from the build-up of deposits in the combustion system, further problems arise with the possible corrosive effect of the sulphur, vanadium, and sodium in residual fuels on the materials of combustion chamber, turbine blades, and heat exchangers.

Little evidence is available about corrosion under running conditions in gas-turbine plant, but laboratory experiments using synthetic combustion gases, have been made at Sunbury and elsewhere to investigate the corrosive effect of sulphur and it was shown that sulphur in the concentrations expected from the combustion of a fuel oil had no appreciable effect on most of the present-day high-temperature alloys. The limiting amount of sulphur which may be tolerated has not been determined, but there is some evidence that the combustion products of high-sulphur-content fuels may cause intercrystalline penetration of certain types of material leading to fatigue failure. Nickel alloys containing less than 18 per cent chromium may suffer high-temperature corrosion if exposed in a reducing atmosphere to combustion gases containing sulphur. This condition does arise in the primary zone of a combustion chamber, particularly around the burner nozzle, but corrosion can be prevented by the use of materials containing a higher percentage of chromium. Corrosion may also occur from sulphur oxides in the low-temperature parts of the system.

In a normal sulphur-containing residual fuel any sodium in the ash generally appears as sodium sulphate in the gas-turbine deposits, and there is some evidence that this salt by itself is without corrosive effect at temperatures below 800° C. Above 800° C corrosion tends to increase rapidly with temperature, and becomes severe as the melting point of the salt is approached at 884° C.

Sodium chloride, or sodium sulphate contaminated with sodium chloride, is more corrosive than the sulphate alone at the same temperature. However, under actual operating conditions sodium, as mentioned above, generally appears in the form of sulphate, and it may react with vanadium in the ash to form sodium vanadates, which are considerably less corrosive than sodium chloride and only slightly worse than sodium sulphate.

Vanadium is probably the most corrosive agent in the fuel, and its effect on some alloys may be serious. In general, corrosion does not start until the melting point of ash is approached, and with vanadium, which is usually deposited as a pentoxide, the melting point is 690° C. There is some evidence that a light coating of vanadium oxide may be as damaging as a heavy deposit, but it has been shown, as already mentioned, that the presence of solid carbon in the hot gas stream—a condition readily occurring with a heavy fuel oil—drastically reduces the extent of deposition of ash. It may be that both deposit formation and corrosion can be reduced or stopped completely by this method.

Conclusions

The desirable characteristics of a fuel for aircraft gas turbines have not yet been fully determined. Research is in progress on this subject, and it has only been possible to give a broad outline of requirements, which are not yet fully backed by adequate experimental data.

From a study of the properties of individual hydrocarbons which may be included in a suitable fuel, certain generalizations concerning straight-run petroleum distillates have been made, and these findings have, as far as possible, been checked by full-scale rig tests.

Fuels of substantially different compositions may be prepared by blending straight-run petroleum fractions, but it is not possible, on the basis of existing knowledge, to combine desirable combustion characteristics associated with the paraffins with the lowest freezing point and maximum economy on a volume basis.

Providing requirements favour a wide-boiling-range type of fuel and the vapour pressure and the freezing point meet specification, this type of fuel should give reasonably good combustion characteristics.

The economic advantages of being able to burn residual fuel oils in industrial and marine gas-turbine plant are considerable, both from the point of view of cost and availability of the fuel.

Before satisfactory operation can be assured with this type of fuel the two problems of ash deposition on turbine blades and heat exchangers and corrosion of the high-temperature parts of the plant have to be solved. Of these two, the more important is probably corrosion, especially as still higher temperatures are needed at the turbine and heat exchangers.

Both problems appear to be linked with the combustion process and the presence of carbonaceous material in the hot gas stream from the burning fuel.

There is no evidence that the refinery will be able to introduce processes for reduction of vanadium and sulphur at cost levels which will allow the residual fuel to remain substantially cheaper than the distillate fuel. For this reason it is necessary for the equipment designer, in conjunction with

the fuel technologist, to develop equipment which will operate satisfactorily on residual fuels of present quality.

ACKNOWLEDGMENT

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SOME CONSIDERATIONS ON THE COMBUSTION IN GAS TURBINES

By J. G. DAWSON *

THE subject of combustion in gas turbines offers potential material for many papers, but it seems appropriate in a symposium of this nature to discuss the relation between the combustion-chamber design and the performance of fuels.

Gas-turbine combustion differs from earlier established forms of continuous combustion in the intensity of combustion, in the range of mass flow conditions over which satisfactory operation is necessary and in the method of introduction of dilution air to reduce the gas temperature to the required value. The increased intensity of combustion involves a greater pressure drop or draught loss than is experienced in, say, boilers, through the necessity for producing sufficient turbulence of the air/fuel mixture to complete the burning in the required space. This pressure drop is undesirable, as it affects the overall efficiency of the equipment, but insufficient is known of the aerodynamic factors controlling the geometry and stability of the flame to allow its reduction at the moment.

The range of conditions over which satisfactory combustion is required is extended, particularly in the case of the aviation gas turbine, by the wide range of altitudes and engine speeds which must be catered for. Various artifices are being used to meet this requirement, the development of special burners having good atomization characteristics over a wide range of fuel flows proving a considerable advantage. Air-blast atomizers are also potentially important in this connexion, but the complication of

* "Shell" Refining and Marketing Co. Ltd., Thornton Research Centre.

the additional air supply is unacceptable, except in some industrial applications. At present the range of conditions is being met without any form of variable air control, but devices of this nature may be necessary in the future. The introduction of dilution air is not peculiar to the gas turbine, the main difference here being the mixing length allowable and the necessity for keeping the mixing pressure drop to the minimum.

The fuels used in all types of gas turbine cover the complete range of possible liquid fuels from gasoline to residual fuels, and include solid fuels such as coal and peat. A single combustion chamber can operate on a wide range of liquid fuels and is, in fact, potentially omnivorous. The design, however, must take account of the characteristics of the fuel to be used, and present combustion chambers developed on one particular fuel cannot necessarily be expected to burn another fuel equally satisfactorily without some modification. Although this has been found to be the case with fuels as close in boiling range as gasoline and kerosine, much can be done to reduce the sensitivity of combustion chambers to fuel characteristics.

The gas-turbine combustion chamber can be regarded as divided into three zones, the zone of fuel preparation and mixing, the reaction zone, and the dilution zone. These zones are not clearly defined and, although it is somewhat of an over-simplification to regard them as separate, it is proposed to do so here for convenience.

In the performance of the combustion chamber, the first zone is the most important, and generally the effects of the characteristics of this zone can be seen in the other two zones. Two means of fuel preparation are in use, by the atomization of the fuel and by its vaporization. The use of vaporizers is restricted to the lighter range of fuels, and as the vaporizers do not produce a homogeneous mixture but depend on further mixing after vaporization, any conclusions regarding the influence of mixing are generally the same for both types. In the main the characteristics of the atomizing type of combustion will be dealt with here.

The mixing is determined both by the airflow pattern in the primary zone as well as by the degree of atomization of the fuel, and for a given air pattern the atomization required is dependent on the fuel properties, particularly the volatility and latent heat of the fuel. The term "atomization" here is used broadly to cover not only the mean drop size of the spray but also the range of drop sizes, the mean cone angle, and the spatial distribution of the spray.

The difficulty of measurement of spray characteristics has restricted the information available on the effect of these, but some progress is now being made in this work in various quarters, and results are being obtained which will assist materially in combustion-chamber design and in the elucidation of the mechanisms involved in combustion.

The main fuel property which affects atomization is viscosity. Density and surface tension also have some influence, but the effects of these are smaller and the variation experienced with practical hydrocarbon fuels is not great. In industrial gas turbines fuels of viscosity as great as 6000 seconds Redwood I at 100° F can be used, but the actual viscosity at the atomizer is reduced in practice to a suitable figure by preheating the fuel. In aircraft fuels the viscosity is very low by comparison with industrial fuels, but it should be remembered that the viscosity can rise considerably

owing to the cooling of the fuel in the aircraft tanks. In long-range aircraft this may cause some deterioration in performance if insufficient attention is paid to the burner characteristics under these conditions.

With hydrocarbon fuels an increase in volatility is found as the viscosity decreases, so that in general any improvement in performance obtained with the lighter fuels is due to a combination of both factors. Modern combustion chambers can digest fuels with a fairly wide range of volatility satisfactorily under conditions of good atomization, but the degree of atomization can be made too great with fuels of higher volatility. In the range of aircraft fuels cases are known where a lighter fuel has given rough combustion, coring, or worse limits for rich blowout than a heavier fuel, this deterioration in performance being overcome by the use of coarser atomization. In practice, this could not be resorted to because of an ensuing decrease in performance under high-altitude conditions, and the real cure is an improvement in mixing in the primary zone. Other cases

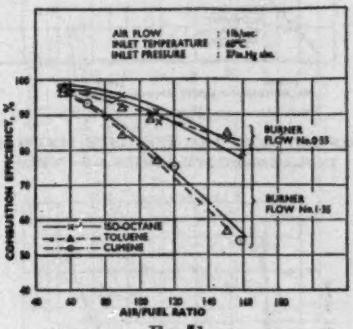

FIG. 1

THE EFFECT OF BURNER FLOW NUMBER ON FUEL PERFORMANCE DIFFERENCES

have been experienced in combustion chambers for industrial gas turbines, where better performance has been obtained on a residual fuel than on a gas oil. In both cases the reduction in volatility and increased drop size and penetration gave better mixing.

The fuel characteristics just discussed are physical, and the effect of these predominates. Where bad atomization is experienced, however, the chemical composition of the fuel can have some effect. Fig. 1 shows results obtained in an aircraft combustion chamber running on *iso*-octane and toluene. These fuels have a similar volatility, but under the conditions of poor atomization a considerable difference in the performance of the fuels can be seen, the *iso*-octane having a considerably higher combustion efficiency at weak mixtures than the toluene. If an atomizer giving a greater degree of atomization is used, however, the difference in performance is practically eliminated. There is some difference in density and viscosity between the two fuels, but little of the difference can be due to this, and one explanation put forward is that the tendency to cracking is less for aromatics than for paraffinic fuels, and that under conditions of bad atomization cracking of the larger droplets to form more volatile

products is a controlling factor. This is confirmed to some extent by the performance of cumene under the same conditions. Although cumene is less volatile and more viscous than toluene, it has a greater tendency to crack, and does, in fact, show a slightly better performance. An alternative explanation can be based on the differences in the latent heats of the fuels. Latent heat has a controlling influence on the life of a droplet, as has been shown by Godsave and Topps.

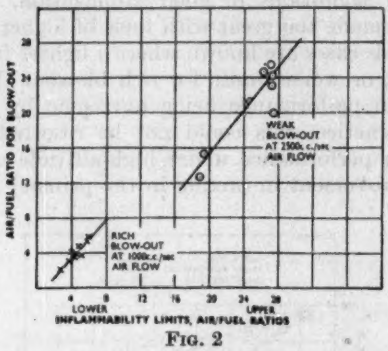
AIR/FUEL RATIO FOR BLOW-OUT
WEAK BLOW-OUT AT 2500 c.c./sec AIR FLOW
RICH BLOW-OUT AT 1000 c.c./sec AIR FLOW
LOWER INFLAMMABILITY LIMITS, AIR/FUEL RATIOS
UPPER

FIG. 2

CORRELATION BETWEEN THE STABILITY LIMITS AND STATIC INFLAMMABILITY LIMITS OF FUELS

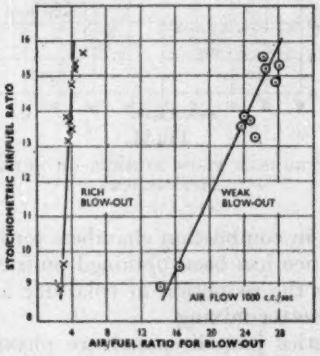

FIG. 3

CORRELATION BETWEEN THE STABILITY CHARACTERISTICS AND STOICHIOMETRIC VALUES OF FUELS

These effects are not solely mixing effects, but true mixing effects can be demonstrated under conditions of vaporized combustion. Work on a small-scale tube with a range of fuels burning under homogeneous conditions has shown that the stability limits correlate well with the static inflammability limits. Fig. 2 shows this correlation, and Fig. 3 shows a similar correlation between stability characteristics and the stoichiometric air/fuel ratios for the fuels concerned. Measurement of the stability limits under non-homogeneous conditions, however, shows that the chemical properties of the fuel can have a considerable effect, other than that due to any

difference in static inflammability limits. Fig. 4 shows weak blow-out curves for the isomers, triptane, and normal heptane, and it can be seen that for certain air velocities a considerable extension of the weak limit is obtained with the more readily oxidizable normal heptane. Curves for *iso*-octane and xylol are also shown, nitrogen being injected with these fuels in order to maintain the same velocities at entry to the combustion system and, therefore, as far as possible, the same initial mixing conditions. It might be expected from these results that addition of agents which affect the rate of oxidation of the fuel would have some effect, but tests in which tetra-ethyl lead was added to the fuel showed only a slight increase in the air/fuel ratio for weak blow-out, or no increase at all. Similarly, tests in which amyl nitrite and di-*tert*-butylperoxide were added showed these to have no effect.

The results were obtained on a small-scale combustion system reproducing the primary zone only of a combustion chamber, and similar effects have

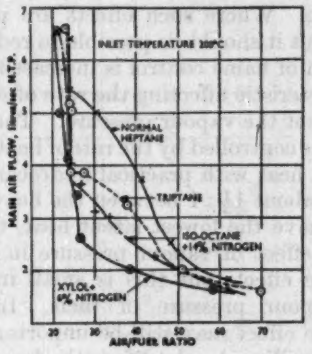

FIG. 4

WEAK STABILITY LIMITS UNDER NON-HOMOGENEOUS CONDITIONS

been shown to be present in a full-scale combustion chamber of the vaporizing type but only in a small degree at atmospheric pressure or above.

It would appear from the results that the controlling factor is the reaction time in relation to the time available for combustion. Reference to Fig. 4 shows that the maximum difference between the fuels occurs at the intermediate velocities covered but that the differences between fuels tend to disappear as the velocity is decreased. In present designs of combustion chambers, the velocities in the primary zone are approaching that for a maximum difference between fuels, but the implication is that if an insensitive combustion chamber is required, reduced velocities are necessary. This is not in line with present trends, and the alternative would appear to be to allow an increased time before quenching occurs.

This brings us to the consideration of the reaction zone of the combustion chamber. In the laboratory flame speed can be taken as a measure of reaction rate, but has little implication in gas-turbine combustion chambers as known at present. When special fuels such as acetylene are excluded, only relatively small variations in flame speed are left between practical fuels, but the over-riding factor is the turbulence which exists in the flame

front. As well as affecting the initial mixing of the fuel and the air, turbulence has two effects, first, by increasing the area of the flame front and, secondly, by increasing the rate at which active bodies are fed back into the unburnt gas. Thus the turbulent rate of burning bears little relationship to the linear flame speed.

In addition to turbulence, fuel-droplet size also affects the rate of combustion, as has been well demonstrated by Topps, Godsave, and others. In general, it has been established that the time of burning of a drop varies as the square of the diameter, so that provided the mixing is adequate the degree of atomization has an important bearing on the standard of performance.

In modern combustion chambers the overall residence time is adequate for the combustion of relatively large droplets of 200 microns diameter and above. This, however, does not necessarily mean satisfactory combustion, as even with adequate mixing quenching can be experienced from wall-cooling air or an excess of combustion air, as well as from the air introduced for dilution. Where such effects are present, differences are shown between fuels, but it should be possible to reduce these as our knowledge of the mechanism of flame control is increased.

The main fuel characteristic affecting the rate of combustion of a droplet is the latent heat and not the vapour pressure. The reason for this is that the rate of combustion is controlled by the rate of heat transfer to the droplet. The variation of latent heat with practical hydrocarbon fuels is not much, there being a range of about $1\frac{1}{2}:1$ between the heaviest and lightest fuels. As the heaviest fuels have the lowest latent heat, there is some degree of compensation for any effect of vapour pressure in practice. The vapour pressure still has some effect, but this is small in comparison with the possible range of vapour pressure of fuels. In aircraft combustion chambers, however, the effect may still be important.

A further factor controlling droplet life is the formation of carbon, either directly from the droplet as in the case of residual fuels or in the flame. The time of combustion of a carbon particle is over ten times that of the corresponding fuel particle and, although the residence time may be sufficient for the complete combustion of the fuel, a carbon particle may be quenched before burning out, with a corresponding combustion loss and the formation of smoke.

It is interesting that, in the case of the aircraft-type combustion chamber, when combustion efficiency is poor, the bulk of the loss is unburnt fuel. This fuel loss is not necessarily unchanged fuel, but it does indicate that quenching has occurred before the complete evaporation of the fuel. Better atomization and a better understanding of the air-flow pattern in the combustion chamber are obviously necessary to eliminate such losses. It would probably be possible to eliminate this loss by increased turbulence, but it is thought that it should be possible by a better understanding of the aerodynamics of combustion to produce the required effect without the increased pressure drop which increased turbulence means at present.

After the unburnt fuel, carbon is the most important source of combustion loss, not necessarily from its magnitude, which is generally small, but from its deleterious effects on flame-tube life and performance. Two types of carbon deposition can be differentiated. First, carbon on the

parallel portion of the primary zone and in the secondary or dilution zones, which might be called downstream carbon, and secondly, carbon on the burners, shrouds, and swirler, which may be called upstream carbon. The former has been studied in detail in many places, and the main factors controlling deposition are fairly clearly understood. Here fuels have widely different tendencies towards deposition, the factors controlling this being the distillation range and carbon/hydrogen ratio of the fuel. Some fuel components, however, can have effects which are out of proportion to their effect on either of these. For distillate fuels of normal composition the specific gravity can be taken as an adequate indication of these two characteristics and gives a good correlation with deposition tendency, as shown in Fig. 5. In all probability the same factors also control the tendency to deposit upstream carbon, but evidence is accumulating that a further factor may also have some influence.

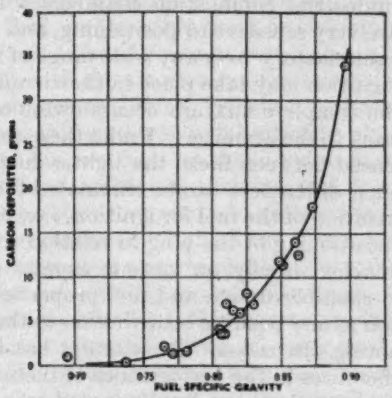

FIG. 5

CORRELATION BETWEEN DOWNSTREAM CARBON DEPOSITION AND FUEL SPECIFIC GRAVITY

Two mechanisms of carbon deposition can be postulated. First, the quenching of burning carbon in the flame and, secondly, the cracking of fuel deposited on hot surfaces with the formation of a carbon residue. It is thought that both mechanisms are present in both types of carbon deposition mentioned, but that the first is preponderant in the case of downstream carbon and the second in the case of upstream carbon.

Downstream carbon usually occurs in the dilution zone and at the entry of wall-cooling air, but is accelerated by bad atomization and flame impingement. Carbon on the burner and swirler is probably due to eddies carrying fuel from the spray on to these parts, but the eddies may also recirculate burning particles.

The cure for downstream carbon is the control of admission of cooling and dilution air and the elimination of flame impingement. In this connexion, the effect of air-entry conditions can be mentioned as an important factor, to which due attention is not always paid. In the case of carbon on the burner and swirler it is not always possible to eliminate any eddies or recirculations, so that it is necessary either to provide a blanketing air

flow across the surfaces involved to avoid the actual deposition of wet fuel or to eliminate the fuel from the recirculation.

Industrial combustion chambers operating on heavy fuels, in general, appear to suffer less from carbon deposition than aero combustion chambers running on distillate fuels, although the fuels are much worse from the point of view of carbon formation. The actual amount of carbon formed in the flame is not necessarily less in the case of the heavy fuels, but adequate measures are taken to avoid its deposition.

One further aspect that has not yet been discussed is starting. Where the ignition is limited owing either to low spark energy or poor fuel preparation, differences will be experienced in the ignition of different fuels. Recent developments in ignition equipment, however, have allowed the supply of sufficient energy for ignition even under the cases of altitude relighting of aero combustion chambers and certainly for the direct ignition of heavy fuels in industrial combustion chambers. These new ignition systems, however, are very sensitive to positioning, and it is difficult to find a position which is satisfactory over any wide range of starting conditions. In some cases local ignition may take place in the vicinity of the spark, but no full ignition of the complete mixture occurs owing to the failure of the flame to propagate back to the atomizer. Under these conditions differences may well be experienced between fuels, the lighter fuels performing more satisfactorily, but such differences can be eliminated for practical purposes by the suitable preparation of the fuel for ignition, *i.e.*, by good atomization and by the correct positioning of the plug in relation to the spray.

This paper has touched briefly on various aspects of the relationship between combustion-chamber design and fuel properties, so briefly that it cannot be looked upon as any positive contribution to the subject but rather as a means of promoting discussion. An attempt has been made to show that many of the differences in the performance of fuels which are apparent in present combustion chambers can be eliminated by suitable design. In the case of the industrial combustion chamber, much of this insensitivity is already apparent, but in the aero combustion chamber the differences in performance due to fuel characteristics are more pronounced. Where differences do occur the physical characteristics of the fuels are of greater importance than the chemical. While it is not likely that the steps necessary to make a combustion chamber insensitive will be taken in the case of the aero combustion chamber owing to the present need for a reduction in combustion-chamber volume and pressure drop, it should be borne in mind that it would be possible.

Much further knowledge is necessary before an adequate understanding of combustion is obtained, but it is suggested that the most pressing need is further work on the aerodynamics of combustion chambers to give more information on the air-flow patterns required for flame stability. The use of variable air-control devices must also be considered. On the fuel side the main work required is an extension of the work on the factors affecting the reaction rate, such as ignition lag, and on the behaviour of fuel sprays as well as single droplets. It must finally be emphasized, however, that the main advances in the gas-turbine combustion chamber are still to be looked for from the combustion-chamber designer rather than from the fuel technologist.

THE DESIGN OF COMBUSTION CHAMBERS FOR THE COAL-FIRED GAS TURBINE

By T. F. HURLEY,* O.B.E.

INTRODUCTION

WHEN considering the fuels which can be used for the gas turbine, oil has many advantages over coal. It can be supplied according to a close specification, it is easy to pump it through pipes, to control its flow by valves, to atomize it, to volatilize it, and to burn it in a small space. It contains little or no ash, and, at least as a distillate, it does not give rise to corrosion or abrasion troubles. Coal, on the other hand, is lacking in uniformity of size or composition, difficult to handle, not so easy as oil to ignite, more difficult to bring into contact with the air required for its combustion, and requires larger combustion chambers. Even " cleaned " coal contains much more ash than does oil, and this gives rise to a host of troubles, starting with the initial preparation of the raw fuel, continuing with harmful deposits in the combustion chamber and on heating surfaces, and finishing, in the case of the open cycle, with possible corrosion and abrasion in the turbine itself.

Most of the disadvantages of coal which have been mentioned, and others apply equally to its use in steam power-plant. Nevertheless, many millions of tons of coal are burned annually under boilers in the U.K., but relatively little oil is so used, mainly because coal is a home-produced fuel and cheaper than oil. To overcome the difficulties of using coal involves elaborate auxiliary plant, high capital charges, high maintenance costs, and unremitting care from the operating staff, yet the overall cost per unit of power generated is, except in special circumstances, lower than with oil.

During the early stages of development of the gas turbine the fuels employed were necessarily the lighter, and more costly, types of oil; and their use was restricted to applications where other factors were more important than fuel cost. Progress in design has led to the use of heavier fuels, and the field is now being extended to include residual oil for turbines for ships and power-plant. At this stage, where the gas turbine is in direct competition with other types of prime mover, fuel costs are of first importance, and the question arises whether a still cheaper, but more difficult fuel, coal, can be utilized in the gas turbine.

An answer to this question is being actively sought in America, where the Locomotive Development Committee of Bituminous Coal Research Inc. have already operated an experimental open-cycle gas turbine on coal with a view to its final application to locomotives, in Switzerland, where Messrs Brown Boveri are stated to have run an open-cycle gas turbine on coal prior to 1944, and Messrs Escher Wyss have designed coal-fired closed-cycle gas turbines of various sizes, and, more recently, in the United Kingdom, where the Ministry of Fuel and Power have given contracts to a number of firms

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for the development of open- and closed-cycle plant to burn coal, peat, and producer gas made from coal. One of these firms, Messrs C. A. Parsons, has already run a gas turbine for a short period on coal. Assistance is being given to the Ministry by various other Government departments, including the Ministry of Supply and the Department of Scientific and Industrial Research, who are dealing mainly with the combustion of coal.

The present paper is concerned only with that part of this work which relates to the design of combustion chambers for raw coal. Coal can be processed by carbonization, gasification, hydrogenation, and hydrocarbon-synthesis to supply liquid and gaseous products, all of which are fundamentally more suitable as fuels for the gas turbine. It is doubtful, however, whether these products can be economic in competition with coal; and as they can be burned in the same types of combustion chamber as those employed for petroleum products, they will not be considered here.

Closed Cycle

Quite apart from any thermodynamic considerations which may render it more suitable than the open-cycle gas turbine for special circumstances, the closed-cycle gas turbine, of which a simple type is shown diagrammatically in Fig. 1, has the great advantage that when coal is used the working fluid is not contaminated with ash, thus avoiding risk of corrosion and abrasion of the turbine blades. For this reason alone some of its advocates suggest that it is the only practicable type of coal-fired gas turbine.

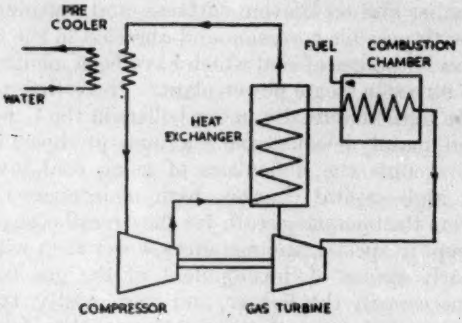

Fig. 1

DIAGRAM OF CLOSED CYCLE GAS TURBINE

From the combustion angle the principal problem is to burn the fuel in such a way as to enable the heat developed to be transferred in a heat exchanger or " air-boiler " to the air going to the turbine. This problem cannot be solved entirely by the direct application of steam-boiler practice, because the temperatures reached in the metal of the air-boiler tubes are higher than in a steam-boiler, and indeed they reach the permissible limit. It is necessary, therefore, to take special care to avoid any risk of flame impinging on the air-heater tubes and other potential sources of local overheating. At one time temperature stresses which might occur in the metal tubes through heating them on one side were thought to rule out radiant

heating, and this consideration led to combustion under pressure to improve the rate at which heat could be transferred by convection. More recently, however, Messrs Escher Wyss decided that the temperature round the circumference of an air-heater tube heated by radiation is more uniform than was originally thought to be the case, and they now advocate the use of radiant heat in a combustion chamber operating at atmospheric pressure.

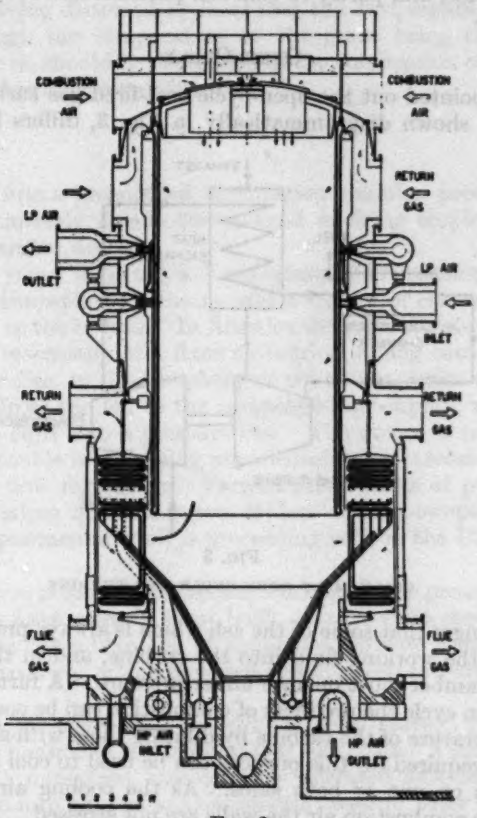

FIG. 2

RADIATION-TYPE HEATER WITH ATMOSPHERIC COMBUSTION (SUITABLE FOR PULVERIZED-COAL OR OIL FIRING) *

In those air-heaters in which the gases leave the combustion chamber at a high temperature, the fact that the metal tubes reach a higher temperature than in a steam-boiler may increase the formation of the external bonded deposits which are giving so much trouble in modern water-tube boilers. These troubles are being actively investigated by the Boiler Availability Committee, whose findings may possibly be applicable to gas-turbine air-heaters. Fortunately the use of pulverized coal is generally unfavourable to the formation of bonded deposits.

* Keller, C., *Trans. A.S.M.E.*, 1950, 72, 845.

Fig. 2 shows an air-heater designed by Messrs Escher Wyss to work at atmospheric pressure and burning sufficient coal to generate 12,500 kW. The combustion chamber is of the vertical, cylindrical, straight-through type, the walls being air-tubes heated by radiation from the flame. A distinctive feature is the recirculation of flue gas at a temperature of 500° to 600° C between the tubes, partly to reduce the mean temperature of the combustion space, and partly to chill ash particles and to blow them away from the tubes.

Open Cycle

As already pointed out the open-cycle coal-fired gas turbine, of which a simple type is shown diagrammatically in Fig. 3, differs from the closed

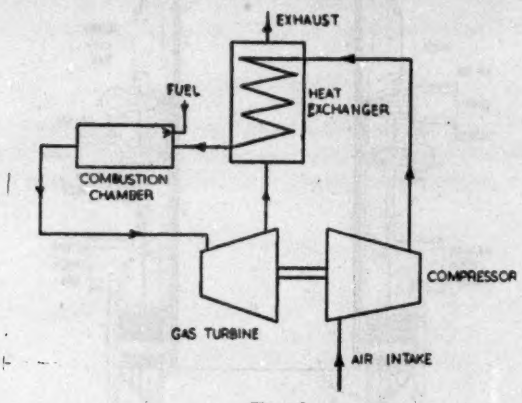

Fig. 3
DIAGRAM OF OPEN-CYCLE GAS TURBINE

cycle in the danger that some of the ash which is always present in coal will be carried by the working fluid into the turbine, and in the fact that the combustion chamber must operate under pressure. A further difference is that in the open cycle the products of combustion can be cooled down to the working temperature of the turbine by diluting them with air, and the large volume of air required for this purpose can be used to cool the combustion-chamber walls on one or both sides. As the cooling air is at the same pressure as the combustion air the walls are not stressed.

Ash

At present there is no known means of causing all the ash in the fuel to be deposited in the combustion chamber, which must necessarily be followed by some form of cleaning device. No dust separator has an efficiency of 100 per cent, particularly when dealing with fine particles, but there is evidence to show that very fine particles having diameters variously estimated as below 5μ and below 15μ may possibly be tolerated by the turbine. As, however, some large particles get through existing types of separator, the combustion-chamber design should be such as to avoid deposits which may be detached from the walls as a result of contraction and expansion and find their way through to the turbine blades.

Deposits may also build up on the walls of the dust separators and fires, and consequent distortion, have been known to occur when the deposits contain a high percentage of carbon. The design of the combustion chamber should therefore ensure that the ash leaving it does not contain more than a certain proportion of carbon—estimated at 20 per cent. A low carbon content is also to be desired because irregularly shaped coke particles may be more abrasive than rounded ash particles.

Apart from being distorted by local fires the dust separator may also be distorted through the temperature of the gases being too high. Combustion, therefore, should be completed in the combustion chamber and the gases cooled either in or soon after it.

Pressurization

To feed coal into a pressurized combustion chamber presents difficulties which may ultimately decide the method of firing employed as well as combustion-chamber design.

The present trend is to use a " coal-pump " to transfer powdered fuel from a bin, at atmospheric pressure, into a stream of compressed air which carries the fuel to the burner. In America the most advanced form of coal-pump consists essentially of a fixed cylindrical casing containing a closely fitting rotating disc, in the periphery of which is a series of cups. These carry the coal from the bin to the compressed-air supply, which blows the fuel out of the cups into a pressure line. The device is not yet fully developed, and trouble is still being experienced with excessive wear, sealing problems, and flow regulation. Various other forms of pump have been suggested, including modified screw feeders and air-swept plunger types, and further experimental work is proceeding both in the U.S.A. and in the U.K.

One alternative is to use a pulverizer working under pressure, and experimental models have already been built. Apart from mechanical details this method has the advantage of employing no new principles, either in construction or control, which have not already been employed with success in boiler work.

The pressure pulverizer may be fed by a " coal-valve," which has a good reputation as a method of feeding granular fuel against a pressure. Fundamentally it is a miniature, mechanically operated lock-hopper system in which fuel is fed into a vessel at atmospheric pressure, after which the vessel is sealed and charged with compressed air. The fuel is then discharged into the pressure system, following which the vessel is again sealed, the residual air discharged to atmosphere, and the cycle repeated. The same principle can be used with large-scale hoppers, but although it is simple and reliable, it involves waste of compressed air.

None of these methods of pressurizing the coal feed affects materially the design of the combustion chamber, but other suggested methods may do so. For example, one approach is to use a producer working under pressure, and this simplifies considerably combustion and combustion-chamber design. Yet another method is to mix pulverized fuel with water to form a thin paste or slurry which can be pumped and atomized like oil. This simplifies pressurization, but not combustion.

Combustion

The fact that the combustion chamber of an open-cycle gas turbine must operate under pressure makes it desirable that the combustion chamber should be of the minimum possible size. Although coal can be pulverized so that the individual particles are comparable in size with the drops in an oil spray, it is far less easy to burn them in a short time, and consequently in a small space.

Quick ignition, close to the burner, can be obtained by using suitable mixture strengths and temperature conditions, and the high preheat used with gas turbines simplifies the process. The difficulty is to bring the air required for combustion into contact with the solid coke residue which remains when the volatile matter in the coal has been burned. Not only are the fuel particles widely dispersed in the air (one volume of coal requires over 12,000 volumes of air for its combustion) but in addition very fine solid particles move at almost the same velocity as the air carrying them. This means that in effect the air has to diffuse through a stagnant film of inert gas to reach the surface of the fuel, and this is a slow process requiring a long " residence time " and thus a large combustion chamber.

This effect is exemplified by the large combustion chambers which were found to be necessary in the first successful pulverized-fuel water-tube boilers using " straight-shot " burners, but in boiler work the need for very large combustion chambers solely to achieve complete combustion disappeared with the introduction of turbulent burners to set up relative motion between the air and the fuel to scrub away the stagnant gas film. In later designs the process has proceeded a stage further, and means have been found to set up controlled relative motion, still further reducing the space required for combustion.

Film-cooled Metal Combustion Chamber

It is believed that the coal-fired open-cycle gas turbine which has at present reached the highest state of development is the experimental unit erected at Dunkirk, N.Y., U.S.A., by the Locomotive Development Committee of Bituminous Coal Research Inc., but even this plant has run only a few hundred hours. Its components, so far as is practicable, are identical with those which will ultimately be fitted to a 4000-h.p. locomotive, and the single coal-fired combustion chamber operates under conditions simulating those of the two which will be used in the locomotive. The present design is the outcome of some years of research carried out at the Battelle Memorial Institute and elsewhere, first to obtain fundamental data on the effect of operating under pressure and on the influence of burner design, fineness of grinding, and type of coal upon combustion, and secondly to design and test practical full-scale equipment.

Effect of Pressure

The work carried out at Battelle has shown that the output of a given combustion chamber is for all practical purposes proportional to absolute pressure; *e.g.*, if the pressure is increased four times, then four times the original output can be obtained without decreasing the efficiency of com-

bustion and without increasing the temperature of the metal walls. Presumably the effect of increased air density on convection cooling compensates for the increased emissivity of the flame at higher pressures.

This conclusion, which has been confirmed elsewhere and is in agreement with the results obtained with oil firing, is of great importance in experimental work, as it enables data obtained at atmospheric pressure to be applied directly to the design of combustion chambers working under pressure. If anything, the test results obtained with higher pressures are better than those which would be predicted from data derived, at atmospheric pressure.

Effect of Fineness of Coal

As might be expected, it has been found that decreasing the size of the fuel particles increases the efficiency of combustion, but this naturally increases the size of the mill required and the power consumed until, with very fine pulverization, the cost becomes prohibitive. It is generally agreed in America that coal ground so that about 90 per cent passes through a 200-mesh sieve represents the best compromise for gas-turbine work. This compares with a figure of about 70 per cent in boiler practice.

Type of Coal

A comprehensive series of tests to determine the effect of type of coal on combustion efficiency is being carried out by the Canadian Department of Mines and Technical Surveys at Ottawa, using a combustion system similar to that employed at Dunkirk. The tests, however, are not yet completed, and only tentative conclusions have so far been drawn from them.

Dunkirk Combustion Chamber

The combustion chambers, developed by and for the Locomotive Development Committee, are of the straight-through film-cooled metal type,

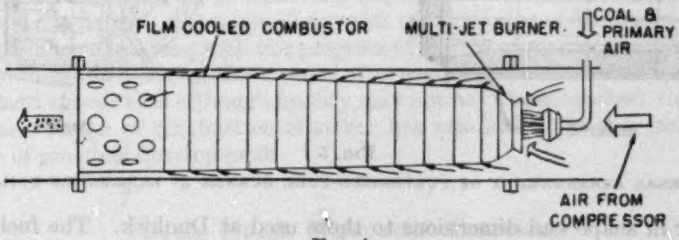

FIG. 4

FILM-COOLED METAL COMBUSTION CHAMBER *

and are designed to burn about 2000 lb of coal per hour at a pressure of about 4 atmospheres. They are constructed of a series of short metal

* Yellot, J. I. Semi-annual report, May–Nov. 1949, to Locomotive Development Committee, Bituminous Coal Research Inc.

cylinders of varying diameter built to form a truncated cone closed at the smaller end by a hemisphere carrying the pulverized-fuel burner. The cylinders are supported by six plates attached to an outer shell, and sufficient cooling air to reduce the temperature of the products of combustion to about 1300° F (700° C) flows between the outer shell and the cylinder to enter the combustion space, partly through gaps between the cylinders, and partly through a number of circular holes at the large end.

Several different models have been constructed, differing in the number and thickness of the cylinders, the width of the gaps between them, the method of support, and so on, but following the general design shown diagrammatically in Fig. 4. When the writer visited Dunkirk, in May 1950, the combustion chamber consisted of thirteen cylinders of $\frac{1}{16}$-inch metal with gaps of $\frac{1}{8}$-inch at the small end and $\frac{1}{16}$-inch farther along the wall, the overall dimensions being 7 ft 6 inches long by 2 ft 6 inches diameter. The quantity of air theoretically required for combustion entered the chamber through or near the burner, about 25 per cent of the total air through the louvres, and the remainder through the large holes at the discharge end.

Burner

The burner is a modified form of the " Multijet " burner designed by the writer for use in Lancashire boilers, of which the combustion chambers are

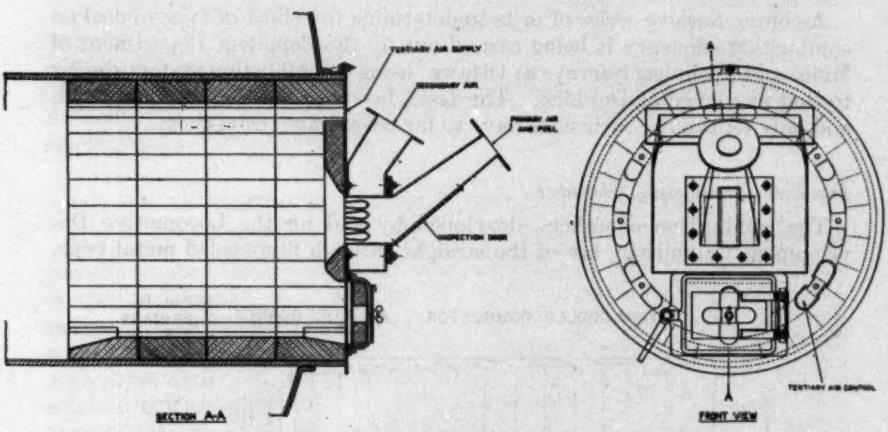

FIG. 5

GENERAL ARRANGEMENT OF PULVERIZED-FUEL BURNER IN LANCASHIRE BOILER

similar in shape and dimensions to those used at Dunkirk. The fuel consumption is also of the same order, allowing for pressure. The theory upon which this burner is based will be briefly described, as it enables a comparatively short flame of the desired shape to be obtained in a small relatively cold combustion chamber. Fig. 5 shows the burner fitted to the furnace of a Lancashire boiler.

The finely ground fuel is carried into the combustion chamber by the appropriate quantity of " primary " air through a number of venturi-shaped square nozzles, the proportion of primary air to fuel being adjusted

to give the most easily ignited mixture. The velocity at which this mixture enters the furnace is such that radiation from the flame and from the combustion-chamber walls ignites the fuel near to the burner face, within an inch or so, before the primary air has had time to mix with any other air supply. When the fuel is ignited it is necessary to supply it with more air sufficiently quickly to prevent the incipient flame being smothered by its own products of combustion, yet slowly enough to avoid chilling it. This additional air is provided as " secondary " air, which enters the chamber round each of the nozzles, and the rate of mixing is controlled by adjusting the relative velocities of the primary and secondary air supplies. At the same time this difference in velocity creates countless small local eddies, thus setting up relative motion between the fuel particles and the air and giving rise to the condition required for rapid combustion. If desired, part of the air can be added at the periphery of the furnace as " tertiary " air, enabling refractory material to be used to maintain a high temperature near the burner for ignition purposes without overheating.

Performance

At the time of the writer's visit to Dunkirk he was informed that the " Multijet " burner had given the highest combustion efficiency of any which had then been tried, generally between 90 and 95 per cent, although a figure of 98 per cent was mentioned. On the other hand, its response to a large decrease in load was not so good as with certain other types, nor as good as would be expected from its performance in Lancashire boilers. The conditions of operation, however, were not those which had been found most suitable in Lancashire boilers. It was proposed to improve the " turn down " characteristics by using a small oil-burner in conjunction with the main coal-burner. The flame did not impinge on the combustion-chamber walls, thus reducing the risk of distortion and slagging; the latest wall construction was free from the distortion experienced with some earlier designs. Fig. 6 shows an example of bad distortion and indicates the extent of the progress which has now been made. The walls of the present chamber were also stated to be uniformly heated and to remain free from any appreciable deposit, but to avoid any risk of aggregates of dust reaching the turbine and interfering with the progress of the experiments, the interior of the combustion chamber was cleaned after each run of a few hours' duration. It would appear that although finality may not have been reached, the Committee's design of combustion chamber has attained at least a promising stage of practical development.

Small Metal Combustion Chambers

In view of the difficulty of burning powdered fuel in very small combustion chambers, considerable interest is attached to experiments proceeding at the E. Pittsburgh Research Laboratory of the Westinghouse Company in which aircraft practice is followed by using small pressurized air-cooled metal combustion chambers. Earlier work on small combustion chambers was carried out by the Battelle Memorial Institute, but abandoned in favour of larger chambers. One Westinghouse experimental chamber, shown

diagrammatically in Fig. 7, consists of a vertical metal cylinder about 40 inches long and 6 inches in diameter closed at the top by a hemispherical dome. Below the dome are two short metal cylinders separated by strips of corrugated metal, followed by a larger metal cylinder perforated by a large number of holes. Pulverized fuel carried by about 20 per cent of the

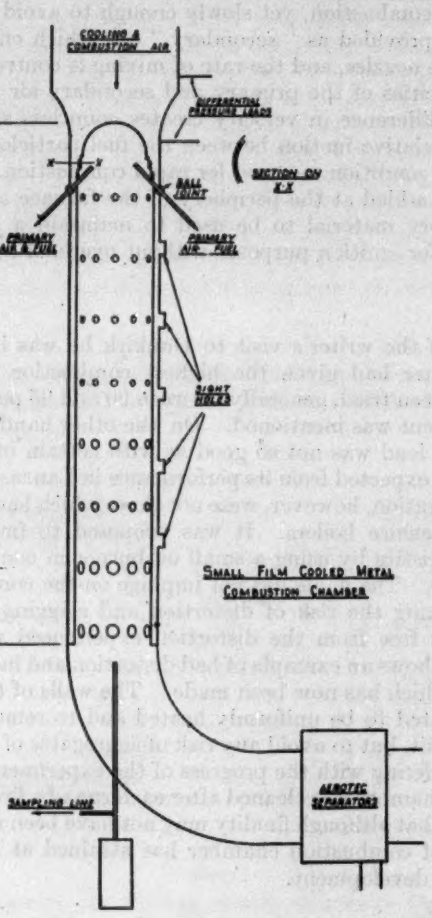

FIG. 7

air required for its combustion is projected upwards into the dome through two inclined pipes, mounted for experimental purposes in ball joints, and the remaining air for combustion and cooling passes between the combustion chamber and the outer casing to enter the chamber through the annular gaps near the top and the holes in the main cylinder. Suitable provision is made for observing the walls through sight holes, for making temperature and pressure measurements, and for sampling.

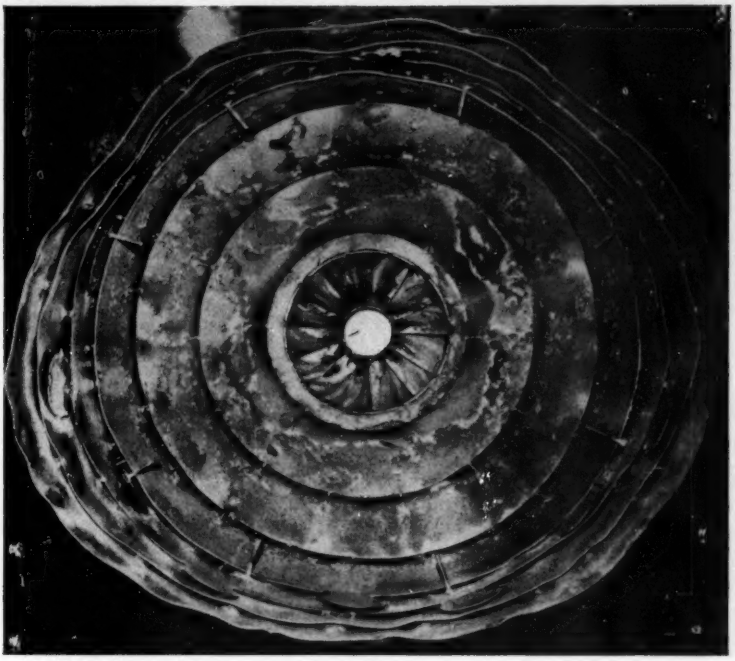

FIG. 6

DISTORTION OF EARLY FILM-COOLED METAL COMBUSTION CHAMBER

Hazard, H. 16A Progress Report to Locomotive Development Committee, Bituminous Coal Research Inc., on combustion of pulverized coal for the gas turbine-driven locomotive.

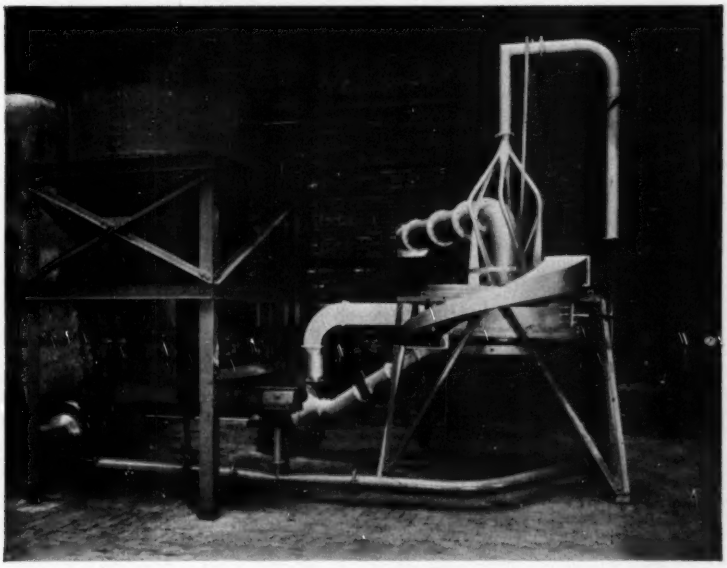

FIG. 12

F.R.S. VORTEX COMBUSTION CHAMBER

[*To face p. 526.*

The chamber has been operated at pressures between 30 and 70 p.s.i. and at loads between 30 and 150 lb of coal per hour, but it was considered to be overloaded at 150 lb/hour. It was said that no trouble was experienced from overheating or from the deposition of partly burned fuel, ash or slag, although at high loads slag built up on the thermocouple and sampling tubes. The maximum combustion efficiency was about 90 per cent at intermediate loads using a coking coal containing 6 to 10 per cent of ash. Fine grinding was found to be advantageous up to a fineness such that 90 per cent passed through a 200-mesh sieve and increasing the pressure improved the efficiency slightly.

Slurry-fired Combustion Chamber

The Westinghouse Company, at their works at South Philadelphia, are also conducting experiments on a large film-cooled metal combustion chamber in which the problem of feeding the coal is solved by mixing the coal

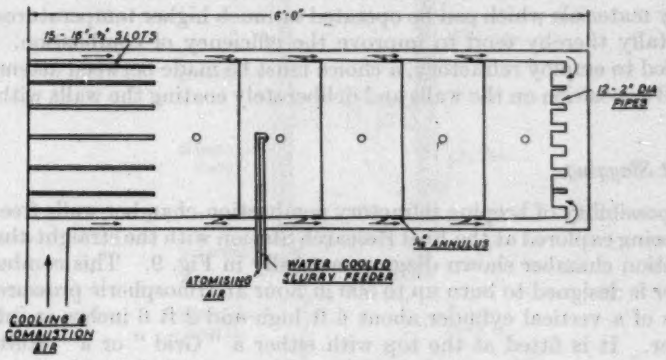

Fig. 8

COMBUSTION CHAMBER FOR BURNING SLURRY

with water to form a slurry which can easily be pumped. The coal, ground so that 90 per cent will pass through a 200-mesh sieve, is mixed with more than its own weight of water in a tank and stirred by a propeller-type mixer. It is then pumped to a second tank, also fitted with a stirrer, from which it is pumped to a nozzle in which it is atomized by compressed air. The nozzle faces upstream in the combustion chamber, of which an experimental model burning about 300 lb of coal per hour at atmospheric pressure is shown diagrammatically in Fig. 8.

The combustion chamber is about 6 ft long with a mean internal diameter of about 20 inches and is cooled by air, preheated to about 400° F (200° C), which passes along a space between the walls and the outer shell and through twelve 2-inch-diameter short pipes in the flat end-plate facing the burner. Cooling air also passes in an upstream direction through four annular slots, $\frac{1}{16}$-inch wide, and through fifteen axial slots 16 inches long by $\frac{1}{2}$-inch wide at the downstream end of the chamber. The products

of combustion are discharged to atmosphere through a refractory-lined duct.

When seen in operation, ignition appeared to be good, in spite of the water content of the slurry, and the flame was small and clear of the walls, but rather ragged and dusty. The offtake was reasonably free from smoke, but a fair amount of sintered coke was ejected in pieces up to 2 inches in diameter by $\frac{3}{16}$-inch thick. Some coke was deposited on the walls, but tended to come off on cooling. The metal temperature was estimated at about 1500° F (800° C) at the tube-plate end, with a dull glow at the rear end. Though this type of combustion chamber requires further development, it is technically promising and provides a possible method of overcoming the problem of feeding pulverized coal under pressure.

Refractory Chambers

One way of avoiding the high cost and constructional and operating difficulties associated with metal combustion-chamber walls is to use refractory materials which can be operated at much higher temperatures, and incidentally thereby tend to improve the efficiency of combustion. If it is decided to employ refractory, a choice must be made between attempting to avoid deposition on the walls and deliberately coating the walls with fluid slag.

Without Slagging

The possibility of keeping refractory combustion-chamber walls free from slag is being explored at the Fuel Research Station with the straight-through combustion chamber shown diagrammatically in Fig. 9. This combustion chamber is designed to burn up to 500 lb/hour at atmospheric pressure, and consists of a vertical cylinder about 6 ft high and 2 ft 6 inches in internal diameter. It is fitted at the top with either a "Grid" or a "Multijet" burner, and apart from external cooling being carried out with air instead of water, the upper part is identical in construction with the arrangement used successfully over a period of years in a large number of Lancashire boilers. In the lower part of the chamber the water-cooled metal walls of the Lancashire boiler are replaced by air-cooled refractory, and to avoid overheating, part of the cooling air is introduced through a number of openings half-way down the chamber.

In practice it has been found possible to avoid slagging, but not the deposition of light, sintered ash on the lower part of the chamber. This ash deposition could not be tolerated in a chamber used as part of a gas-turbine unit, and, though further experiments are proceeding, consideration is being given to a design which will combine the advantages of using a refractory lining in the top part of the chamber with those of film-cooled metal in the lower part. The existing chamber is flexible and easy to operate, and the combustion efficiency is reasonably high (about 95 per cent).

Slagging

In the slagging type of straight-through combustion chamber the ash in the fuel is deliberately brought into contact with the refractory walls, which

are maintained at a high temperature such that the ash fuses on them and runs down in the form of fluid slag. The ash, therefore, does not agglomerate on the walls, and by chilling it as it leaves the combustion chamber, a large proportion can be removed in an easily handled condition, thus reducing the load on the dust-extraction plant. The last advantage is limited, however, by the fact that the same volume of gases must be handled, and even in a slagging chamber they will carry fine dust which is difficult to remove.

For successful operation the combustion chamber must be designed to

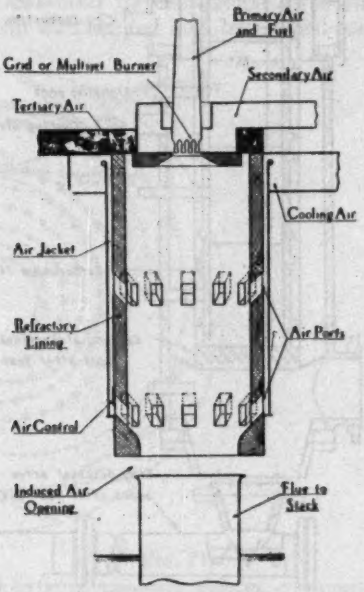

FIG. 9

STRAIGHT-THROUGH COMBUSTION CHAMBER

avoid wastage, cracking, or spalling of the refractory with varying loads, and the slag must not be allowed to freeze at low loads or when using coals containing ash having a high fusion point. In addition, care must be taken to prevent any part of the chamber becoming sufficiently cool for the ash to stick without running. It is also undesirable to form small fused agglomerates which might cause serious wear if they found their way into the turbine.

Fig. 10 shows diagrammatically an experimental slagging combustion chamber which has been tried by the Locomotive Development Committee. The air entering the chamber at the top is given a swirling motion and throws the coarse powdered-fuel particles into contact with the carborundum walls, which become coated with a thin layer of slag. Any new slag runs down the walls, and on being chilled at the base with cooling air forms " stalactites," which drop off into a hopper leading to an ash-disposal screw. The

writer was informed that the carborundum walls did not become wasted or cracked and that the combustion efficiency was high (over 96 per cent), but

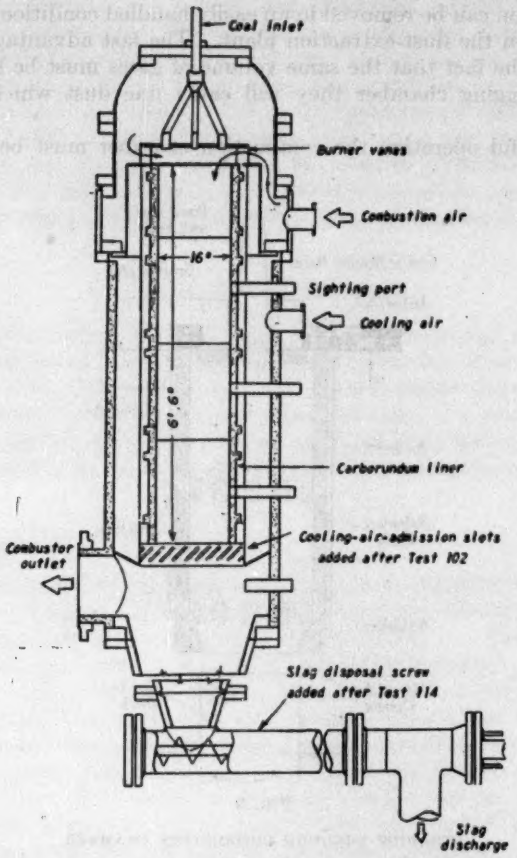

FIG. 10

SLAGGING STRAIGHT-THROUGH COMBUSTION CHAMBER *

work on this model was suspended to allow other promising types of combustion chamber to be tested.

"VORTEX" COMBUSTION CHAMBER

It will be remembered that one of the main problems in designing a small combustion chamber to burn powdered coal is to provide means to obtain relative motion between the air and the coal. In the "vortex" combustion

* Hazard, H. 16A Progress report to Locomotive Development Committee, Bituminous Coal Research Inc., on combustion of pulverized coal for the gas turbine-driven locomotive.

chamber an attempt is made to obtain *controlled* relative motion to speed up combustion by scrubbing away the stagnant film surrounding the coal particles.

The first combustion chamber of this type was designed by the writer in 1929, following an observation by Dr C. H. Lander, then Director of Fuel Research. In order to examine the flow pattern in a free vortex, Dr Lander introduced a thin slurry of red lead and water into a vessel containing water rotating as a free vortex. He observed that some of the red-lead particles did not travel to the centre with the water, but rotated in circles at a constant distance from the axis. It was concluded that the inward drag of the water on the particles was balanced by centrifugal force and that if the water could be replaced by air and the red lead by ignited coal particles, then the

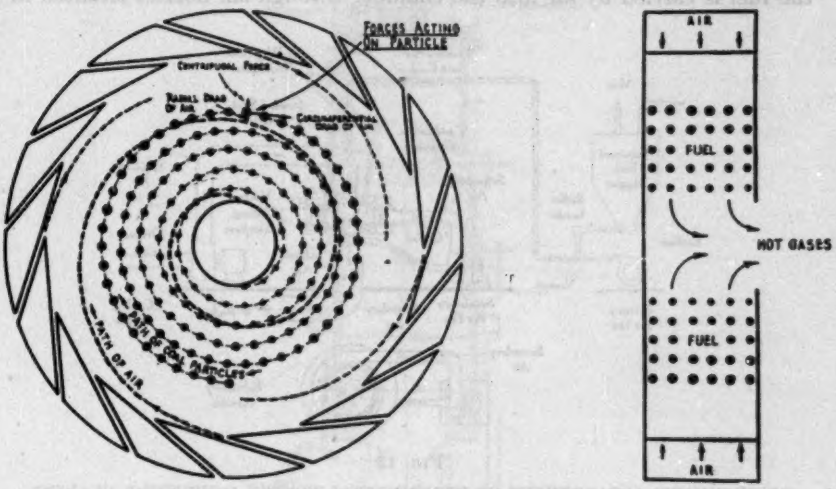

FIG. 11

FLOW OF AIR AND FUEL THROUGH VORTEX COMBUSTION CHAMBER

inward flow of the air across the path of the coal particles would give the scrubbing action required for rapid combustion. The principle is illustrated diagrammatically in Fig. 11.

This idea was first tried with the object of burning coal in either a refractory or a water-cooled precombustion chamber intended to be fitted to a Lancashire boiler, but development was suspended because satisfactory results were obtained more quickly with the "Grid" and "Multijet" burners, which were developed at about the same time. It is of interest, however, to note that the first combustion chamber used at the Battelle Memorial Institute in their locomotive gas-turbine programme was an air-cooled vortex chamber, and that this was employed in 1946 in the first improvised gas turbine to run on coal in America.

It was concluded from the American experiments that the vortex combustion chamber is capable of a very high heat release (a figure of 3 million B.Th.U/cu. ft/hour was achieved), but it required further development with regard to ignition and "turn-down" characteristic. The work was sus-

pended at an early stage to permit comparative tests on straight-through chambers and has not been resumed. More recently in Britain the National Gas Turbine Establishment have achieved promising results using this method to burn residual oil in an air-cooled combustion chamber, and work on the use of coal is being carried out at the Fuel Research Station with a view to its application to the gas turbine.

The general arrangement of the experimental plant at the Station is shown in Fig. 12, and its layout is shown diagrammatically in Fig. 13. The combustion chamber is approximately 3 ft in diameter and 1 ft 3 inches deep. The dished top and bottom walls are of air-cooled heat-resisting steel, and the circumferential wall of firebrick. The main air for combustion enters tangentially through sixteen slots formed in the refractory wall, and the fuel is carried by air into the chamber through six nozzles situated in

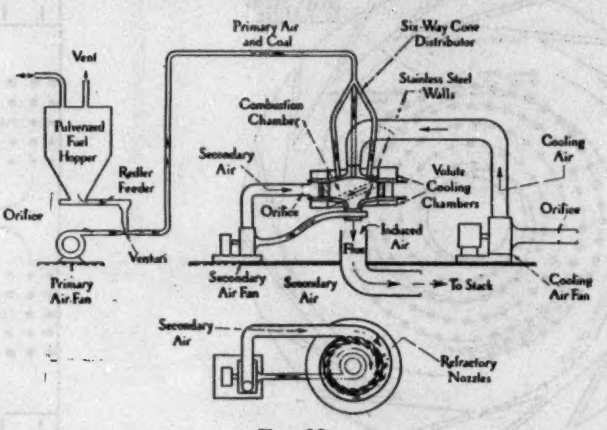

FIG. 13

DIAGRAMMATIC ARRANGEMENT OF EXPERIMENTAL VORTEX COMBUSTION CHAMBER UNIT

the top wall. The products of combustion leave through a central orifice in the bottom wall, and are for convenience discharged into an underground flue leading to a chimney. It is possible to burn 500 lb of coal per hour in the chamber at atmospheric pressure and to obtain a combustion efficiency exceeding 90 per cent. Attempts are now being made to increase this efficiency and to overcome a tendency for a small central patch of the top plate to overheat.

"CYCLONE" COMBUSTION CHAMBER

In the "Vortex" combustion chamber every endeavour is made to avoid the deposition of ash and the formation of slag in the combustion chamber. By contrast, although it is also sought to get controlled relative motion between the air and the fuel, the "cyclone" combustion chamber which is being developed under a DSIR contract by the British Coal Utilization Research Association is designed to collect as much ash as possible in the chamber itself and to remove it as liquid slag. In principle the BCURA

plant resembles the well-known cyclone combustion chamber applied to water-tube boilers by Messrs Babcock and Wilcox, but is arranged with a vertical axis instead of one slightly inclined to the horizontal. The horizontal type is being investigated in Canada by the Department of Mines and Technical Surveys.

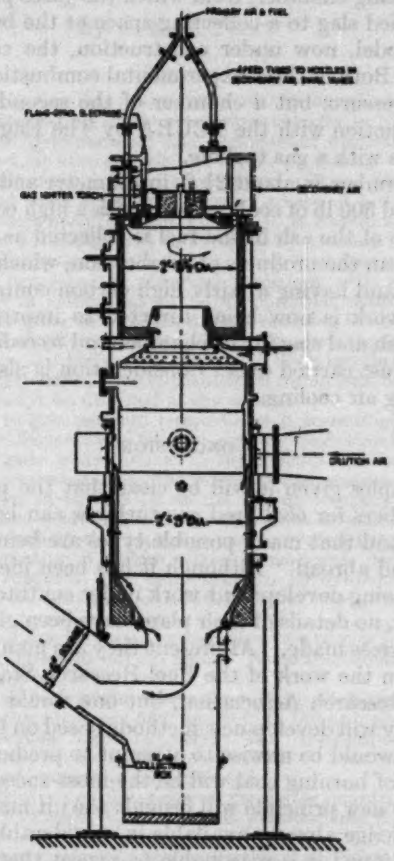

FIG. 14

CYCLONE COMBUSTION CHAMBER *

In the BCURA experimental plant, shown diagrammatically in Fig. 14, the air for combustion enters the periphery of the cylinder tangentially at the top and passes downwards with a swirling motion towards an offtake throat situated centrally in the base. Granular fuel (below $\frac{1}{16}$-inch) is introduced at the top and is thrown by centrifugal force into contact with the walls, which are covered during operation with a film of molten slag. This retains the fuel particles until they have been burned by the scrubbing action of the air.

* Courtesy British Coal Utilisation Research Association.

The walls are of water-cooled refractory and are designed to waste away until they reach an equilibrium condition with the inner slag coating, which is constantly renewed by more ash as the previously deposited ash fluxes and runs down the walls to an overflow in the base. On leaving the combustion zone the products of combustion and the ash are chilled by cooling air in a special cooling chamber, from which the gases pass to a dust separator and the solidified slag to a collecting space at the bottom.

In a second model, now under construction, the combustion products leave at the top. Both of these experimental combustion chambers operate at atmospheric pressure, but a chamber of the second type has also been designed in conjunction with the BCURA by The English Electric Co., for use under pressure with a gas turbine.

The present chamber is about $2\frac{1}{2}$ ft in diameter and 10 ft high and has successfully burned 500 lb of coal per hour with a high combustion efficiency. About 85 per cent of the ash in the fuel is collected as slag, but it will still be necessary to clean the products of combustion, which carry dust covering a wide size range and having a fairly high carbon content.

Experimental work is now being directed to improving the method of dealing with the ash and slag in the chamber and to reducing the percentage of carbon in the dust carried over. Consideration is also being given to the possibility of using air cooling.

Conclusion

From the examples given it will be clear that the problem of designing combustion chambers for coal-fired gas turbines can be approached from a variety of angles and that many possible types are being investigated, both in this country and abroad. Although it has been mentioned that several British firms are doing development work under contracts from the Ministry of Fuel and Power, no details of their plant have been given, as it is too early to discuss the progress made. At present they are mainly using combustion chambers based on the work of the Fuel Research Station and the British Coal Utilisation Research Association, but one would expect that as their work proceeds they will develop new methods based on their own experience.

At this stage it would be unwise to attempt to predict which of the many possible methods of burning coal will be the most successful, and it may be that some entirely new principle will provide the ultimate solution. Nevertheless, the knowledge already available is considerable, and if the present effort can be continued it is reasonable to expect that the construction of a practicable coal-fired gas turbine will not be delayed by considerations relating to combustion-chamber design.

Acknowledgments

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AN EXPERIMENTAL STUDY OF THE EVAPORATION AND COMBUSTION OF FALLING DROPLETS

By J. E. C. Topps *

Summary

A general investigation has been made of the evaporation of droplets 300 to 500 μ diameter falling at their terminal velocity in high-temperature atmospheres. Pure hydrocarbons, and commercial distillate and residual fuels, were employed, at atmospheric and higher pressures.

Quantitative results for the pure hydrocarbons, obtained by measurement of residues collected upon solid CO_2, showed a rate of evaporation dm/dt, which varied approximately as radius $^{1\cdot5}$. It is concluded that in gas-turbine practice less advantage will be obtained by securing fine atomization than is to be expected from simple theory, which suggests $(dm/dt)\ \alpha\gamma^{2\cdot5(3\cdot5)}$.

The discrepancy between the observed variations with radius and that predicted as above is considered to be accountable mainly through the conduction of heat to the interior of the droplet reducing the heat available for the evaporation of the smaller droplets. Theory suggests that the temperature of the vapour leaving the surface of the droplet boundary layer is below the ambient level, and dependent upon experimental conditions, but that ambient temperature can always be attained in the wake.

Transfer of heat to give ambient temperature is accordingly considered in terms of the energy dissipated as friction, and an approximate correlation of the evaporation of pure hydrocarbons in these terms has been obtained for ambient temperatures exceeding the boiling temperatures by $>200°$ C, assuming the droplet surface to be at the boiling temperature. At lower ambient temperatures a lower surface temperature is attained, apparently that which corresponds to the vapour pressure needed for the removal by diffusion of that quantity of vapour whose formation is permitted by heat transfer. Theory suggests that the variation of evaporation rate with temperature is affected also by the outward flow of vapour from the droplet surface reducing the transfer of heat to it.

The results for kerosine indicated evaporation at a rate as for a pure hydrocarbon boiling at the normal bubble point. Some fractionation or cracking occurred with the gas oil.

Droplets of residual fuels of maximum size ~ 280 μ all showed a tendency to swell at air temperatures between 680° and 800° C, but at higher temperatures small coke-like residues were obtained. The low-temperature swelling appears to be accountable in terms of conduction of heat to the interior of the droplet. Photomicrographs are presented.

Experimental difficulties at high pressure precluded quantitative treatment of the results. It appeared, however, that pressure had little effect upon the evaporation rate.

In no case has the investigation been exhaustive, and more work is needed, in particular to investigate the behaviour of heavy fuels.

Introduction

The work described here is part of an attempt being made to obtain a better understanding of the manner in which a fuel spray injected into a gas-turbine combustion chamber is burned. Practical application requires that the experiments are undertaken with droplet sizes similar to those used in practice, moving with terminal velocity relative to the air.

Under these conditions combustion would, however, be complete in too short a time for observation. Combustion of volatile liquids takes place

* National Gas Turbine Establishment, Ministry of Supply.

as a diffusion flame, however, so that the heat release occurs at a plane surrounding the droplet where a stoichiometric mixture of air and fuel vapour is formed by diffusion. The flame accordingly acts only as a source of heat, which has to be conducted to the droplet surface and, hence if radiative heat transfer is negligible (which may be assumed for all but black fuel oils) the flame may be replaced by a hot gas atmosphere of such temperatures that the evaporation of the droplet may be studied conveniently.

Many workers have studied the evaporation of droplets, principally at low temperatures and using suspended droplets. No experiments may be cited, however, where the rate of evaporation is so great that it may be compared with a burning rate, nor where evolution of vapour from the droplet surface or conduction of heat to the interior can influence the result significantly.

Accordingly, the evaporation of freely falling droplets has been studied as permitting a closer approach to the conditions existing in practice, and to those where the above processes may have a crucial effect.

The results of the investigation are described below.

General Theory of Evaporation Rate

The evaporation rate of droplets has been studied theoretically by Fuchs [1] and experimentally and theoretically by Frössling.[2] In his treatment Frössling obtained a theoretical relation calculated from the equation of diffusion in a moving medium, and obtained the relation

$$\frac{dm}{dt} = \frac{4\pi\Delta Mp}{RT} r(1 + K\sqrt{Re}) \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Thus rate of evaporation in a moving air stream varies as diffusion coefficient, radius, partial pressure, and a complex function of Reynolds number, K being a constant whose value varies with each particular substance, and is generally approximately 1/3.

In his description of his experimental results he records the difference between droplet and ambient temperatures. This difference in temperature must be that which permits the transfer of heat to the droplet necessary for the latent heat of evaporation. This conduction of heat must occur under any condition of evaporation, and the evaporation rate of a drop may be calculated provided this temperature difference and the conductance of the boundary layer is known, if it may be assumed that the outward flow of vapour does not influence the conduction of heat, and the drop temperature is uniform and steady.

From Gumz's [3] work, variation of droplet terminal velocity with radius may be estimated, and Eckert [4] gives a variation of boundary-layer thickness with radius and Reynolds number. Accordingly, the variance of boundary layer conductance with droplet radius may be estimated as follows:—

Droplet surface $\propto r^2$

Terminal velocity $\propto r^2 (r^{1.6})$

$\therefore$ Reynolds number at terminal velocity $\propto r^3$ $(r^{2.6})$

Assuming Eckert's relation is valid at low Reynold's numbers obtaining under the experimental conditions.

Boundary layer thickness $\propto \dfrac{r}{\sqrt{Re}}$

$\therefore$ Boundary layer thickness at terminal velocity

$$\propto \frac{r}{\sqrt{r^{3.0}}} = r^{-0.5} \; (r^{-0.3})$$

$\therefore$ Boundary layer conductance at terminal velocity

$$\propto r^{2.0}/r^{-0.5} = r^{2.5} \; (r^{2.3}) \quad . \quad . \quad . \quad . \quad (2)$$

This conductance may be shown to vary only slightly with temperature, at a given drop size. Since kinematic viscosity varies as $T^{1.5}$, Reynolds number (at constant velocity) varies as $T^{-1.5}$, and boundary layer thickness as $T^{0.75}$. The thermal conductivity of gases varies as slightly more than $T^{0.5}$ on account of the increase in specific heat, so little change in conductance with temperature is to be expected.

The diffusion of vapour from the drop surface varies likewise with change in drop radius and temperature. Change in drop-surface area and boundary-thickness will influence the diffusion rate in the same manner as conductance of heat. Change in temperature also influences the transport of material similarly, the change in diffusion coefficient effectively cancelling the effect of the thickening of the boundary layer.

The validity of these conclusions depends, however, upon there being no effects due to the outward flow of vapour from the droplet and its attaining a steady and uniform temperature. Experimental confirmation is necessary for the conditions where these effects are likely to be greatest, that is for very short evaporation times.

Experimental Determination of Evaporation Rate

Choice of Method

Evaporation of drops for very short times can be arranged in one way only—by allowing them to move through a hot atmosphere, under such conditions that their change in size can be measured. Small drops are to be preferred, so that terminal velocity conditions are most readily obtained. This creates a problem of measurement, for not only is greater absolute accuracy required but as small drops are readily deflected by any air current, photographic magnification is impracticable, and their residues must be collected. Weight measurement of residues requires the use of a micro-balance, and the operating time would be impracticable with volatile material. Collection on aerosol-coated slides is also unsatisfactory unless their temperature can be closely controlled.

No ideal solution to these practical problems was found, but experiment showed that when drops of some liquids fell upon a solid CO_2 surface their shape remained spherical so that their size might be estimated from microscope measurements. This is the method employed in the experiments to be described, and measurements of evaporation rate were carried out with

α-methylnaphthalene, indene, and *p*-xylene on account of their suitability in this respect.

This method is, nevertheless, limited in its application since well-defined drops of many liquids, *e.g.*, dodecane, could not be obtained, and in no case could sizes exceeding 600 μ be obtained. Moreover, rapid measurement was necessary, on account of frost; hence the use of high-power objectives was precluded, thus limiting the accuracy of measurement, so that droplets of initial diameter less than 250 μ could not usefully be employed. Also evaporation of the solid CO_2 precluded reliable focusing, so photographic methods could not be employed.

Apparatus and Experimental Procedure

The features of the apparatus significant to consideration of the results are apparent from superficial examination of Fig. 1. The atomizer is a simplification of that developed by Lane,[5] made possible by the technique of direct measurement employed, and originally constructed on account of the advantage obtainable in the handling of viscous liquids by heating the air. For satisfactory operation precision manufacture and erection are necessary: failing this, provision must be made for calibration *in situ*.

It was found necessary to insulate thermally the water-cooled tube in order to obtain uniform air-temperature distribution, and to eliminate the flow of air in either direction through the droplet admission tube, as this could double or halve the evaporation rate observed. This was effected by admitting and withdrawing from the furnace equal quantities of air. A downward flow of velocity approximately 1 inch/second was used to prevent accumulation of vapour. Some work was also attempted at high pressure. Though the production of uniform droplets was achieved with little trouble, rapid condensation of moisture precluded the use of solid CO_2, so aerosol-coated slides were employed. The need for rapid operation at high pressure necessitated the storing and photographing of the slides, so some trouble from evaporation was encountered, as well as that arising from the effect of temperature. Accordingly, only qualitative results could be obtained, and the experiment was not pursued.

TABLE I

I.P. Distillation Data

	Kerosine	Gas oil
I.B.P., °C	158·0	210·0
5%	171·0	235·0
10%	180·0	245·0
20%	190·0	260·5
30%	198·0	269·5
40%	206·0	276·5
50%	215·0	283·0
60%	225·0	289·5
70%	235·0	297·0
80%	246·5	306·0
90%	262·0	319·0
95%	274·0	329·5
F.B.P., °C	287·5	343·0
Total distilled, %	99·0	98·5
Normal bubble pt. at 1 atm, °C	186	259

The experiments were conducted using the following pure substances: α-methylnaphthalene, b.p. 240° C; indene, b.p. 182° C; *p*-xylene, b.p. 137° C. A kerosine and a gas oil, of I.P. distillation as shown in Table I, were also used, the latter for qualitative work only.

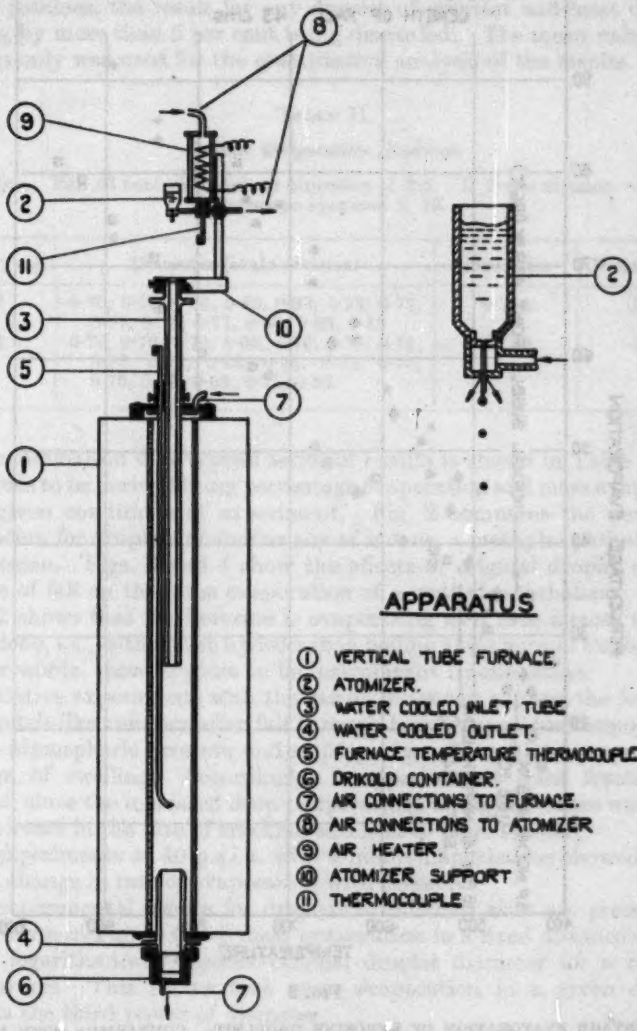


FIG. 1

It was found that residues could be collected after droplets had fallen through air at temperatures of up to about 400° C above their boiling temperature. Experiments with various droplet sizes and distance of fall were carried out with α-methylnaphthalene only.

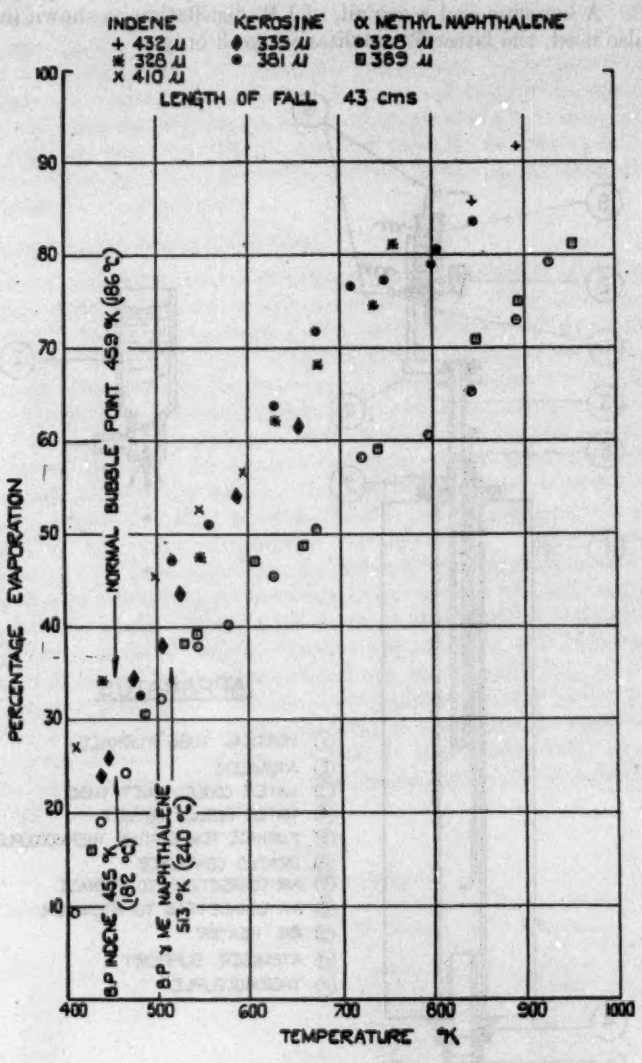


FIG. 2

PERCENTAGE EVAPORATION OF KEROSINE DROPLETS. COMPARISON WITH INDENE AND α-METHYLNAPHTHALENE

Results of Experiments

The results of the quantitative experiments were in the form of measurements of diameter of the residues collected on solid CO_2. A typical selection is given in Table II. The values given are of mean diameter of individual droplet residues, the result for any droplet of greatest and least diameter differing by more than 5 per cent being discarded. The mean value of the readings only was used for the quantitative analysis of the results.

TABLE II

Droplet Evaporation Readings

Kerosine. Fall 43 cm. Microscope objective × 3·5. 1. Scale division = 432 μ. Microscope eyepiece × 10.

Temp (° C)	Diameter (scale division)	Mean dia	Mean dia (μ)
17	0·80, 0·75, 0·80, 0·80, 0·83, 0·78, 0·77, 0·77, 0·75, 0·77, 0·80, 0·85, 0·85	0·794	346
172	0·70, 0·70, 0·70, 0·69, 0·70, 0·70, 0·71, 0·76, 0·72, 0·68, 0·75, 0·75, 0·75, 0·70, 0·73, 0·68, 0·72, 0·65	0·710	313

The examination of a typical series of results is shown in Table III, the first values to be derived being percentage evaporation and mass evaporation under given conditions of experiment. Fig. 2 compares the percentage evaporation for droplets of similar size of indene, α-methylnaphthalene and the kerosine. Figs. 3 and 4 show the effects of original droplet size and distance of fall on the mass evaporation of α-methylnaphthalene.

Fig. 2 shows that the kerosine is evaporating at a rate almost identical with indene, *i.e.*, with a pure hydrocarbon boiling at its normal bubble point. In other words, there appears to be insignificant fractionation.

Qualitative experiments with the gas oil, however, showed the formation of soft pitch-like residues after fall through high-temperature atmospheres, both at atmospheric pressure and at 55 p.s.i.a. In neither case was there any sign of swelling. Accordingly, it appears that some fractionation occurred, since the increased drop temperatures at high pressure would lead to an increase in the rate of cracking and lead to more swelling.

The experiments at 40 p.s.i.a. with α-methylnaphthalene showed no significant change in rate of evaporation with pressure.

The experimental results for droplets of different sizes are presented in another form in Fig. 5, where mass evaporation in a fixed distance of fall is plotted logarithmically against original droplet diameter for a range of temperatures This shows that mass evaporation in a given distance varies as the third power of diameter.

A more precise treatment of the results is given in subsequent sections of Table III. Heat transfer is generally considered in terms of Reynolds number, but the application of this concept must be approximate on account of the continuous reduction in size and velocity of the droplets. The physical effect of which Reynolds number is a criterion is, however, viscous friction. The energy released as friction when a body falls through a given

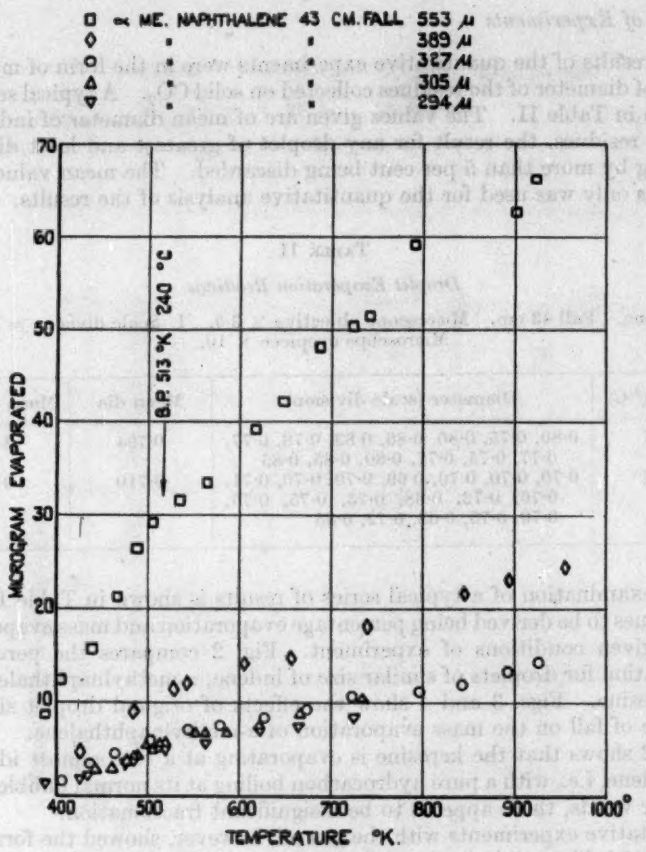


FIG. 3

VARIATION OF DROPLET EVAPORATION WITH DIAMETER

TABLE III

Calculations of Results

α-Methyl naphthalene . . . Original diameter 331 μ (7·75 div.). Mass 18·9 μg.
Length of fall . . . 31 cm. Gross potential energy 0·575 ergs.
Initial temperature . . . 20° C. Kinetic energy at entry 0·133 ergs.

Furnace temp, ° K . . .	437	519	595	641	722	734	746	826	877
Outlet diameter, μ . . .	322	297	285	278	263	263·5	255	239	222
Mass evaporated, μg . . .	1·6	5·3	6·8	7·8	9·5	9·4	10·2	11·8	13·2
Potential energy of vapour, ergs .	0·025	0·085	0·113	0·129	0·161	0·159	0·176	0·208	0·240
Kinetic energy at outlet, ergs .	0·115	0·059	0·046	0·038	0·018	0·018	0·014	0·009	0·007
Net frictional energy, ergs . .	0·568	0·546	0·549	0·541	0·519	0·521	0·518	0·491	0·461
Evaporation, μg/erg . . .	2·8	9·7	12·4	14·4	18·3	18·1	19·7	24·0	28·6
Heat transfer to give vapour and residue at 513° K, ergs . .	—	99,100	107,000	112,100	119,500	119,000	123,000	130,600	137,200
Heat to raise vapour to ambient temperature, ergs . . .	—	750	13,450	21,950	48,700	52,100	62,400	104,600	140,800
Total heat transfer, ergs . .	—	99,850	120,450	147,050	168,200	171,100	185,700	235,200	278,200
Heat transfer, erg (friction), deg .	—	30,300	2,680	2 103	1,552	1,490	1,655	1,525	1,655

height is equal to the difference between the sums of kinetic and potential energy before and after the event, and is dissipated partly as viscous friction and partly in overcoming form drag. In the absence of heat transfer and evaporation there is a constant distribution of energy between the above processes at low Reynolds numbers, and it may be assumed that this is also true in their presence. The rate of evaporation is expressed in

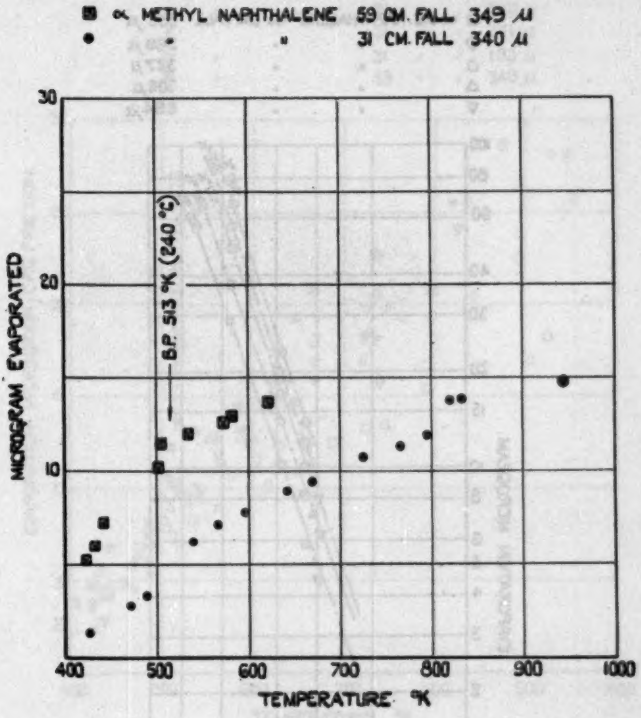


FIG. 4

VARIATION OF DROPLET EVAPORATION WITH LENGTH OF FALL

terms of the total friction, as comparative values only are needed for the subsequent analysis.

Proportionality between heat transfer and friction was originally proposed by Reynolds [6] in 1874, but his simple correlation was imperfect. More complex relations proposed by Prandtl,[7] and von Karman,[8] applying to flow through pipes, though sufficiently accurate to justify the analogy, could not be applied to the present experimental results.

The change in potential energy was readily calculable from the experimental results, as the length of the inlet to the furnace was adequate for the approximate attainment of terminal velocity of the droplets which was assumed at inlet and outlet for the calculation of the change in kinetic energy, using Gumz's [3] values. The potential energy of the vapour was

subtracted from the overall difference, as once the vapour is formed it contributes no further energy. An expression was derived for the centre of gravity of the vapour from the observation that the percentage evaporation of a given liquid for a given height and temperature was approximately independent of the original size of the droplet.

Fig. 6 shows that the relation between mass evaporation and friction varies negligibly with distance of fall, and only slightly with original drop

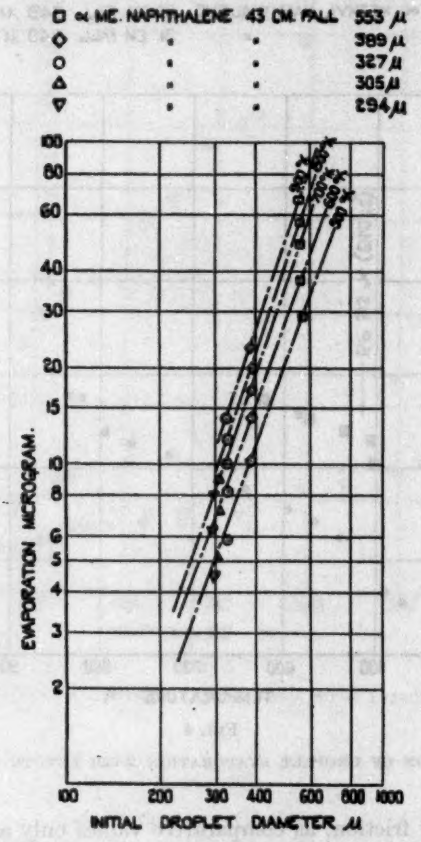


FIG. 5

THE VARIATION OF DROPLET EVAPORATION WITH DIAMETER

size at any given temperature. The latter variation could be reduced to within the limits of experimental error by dividing the mass evaporated per erg friction by diameter$^{-0.3}$. The results adjusted to an arbitrarily chosen "standard" diameter of 330 μ are shown in Fig. 7, and it appears that a unique relation exists between (evaporation/friction) and temperature.

The above treatment is considered to give the most exact expression of the experimental results practicable. Since the frictional energy developed during the fall of the droplet depends mainly upon the original mass and

distance of fall, the result is equivalent to that shown in Fig. 5. According to Gumz, the terminal velocity of droplets of the sizes used in the experiments varies as a power of radius of the order of 1·6–2·0. If this relation

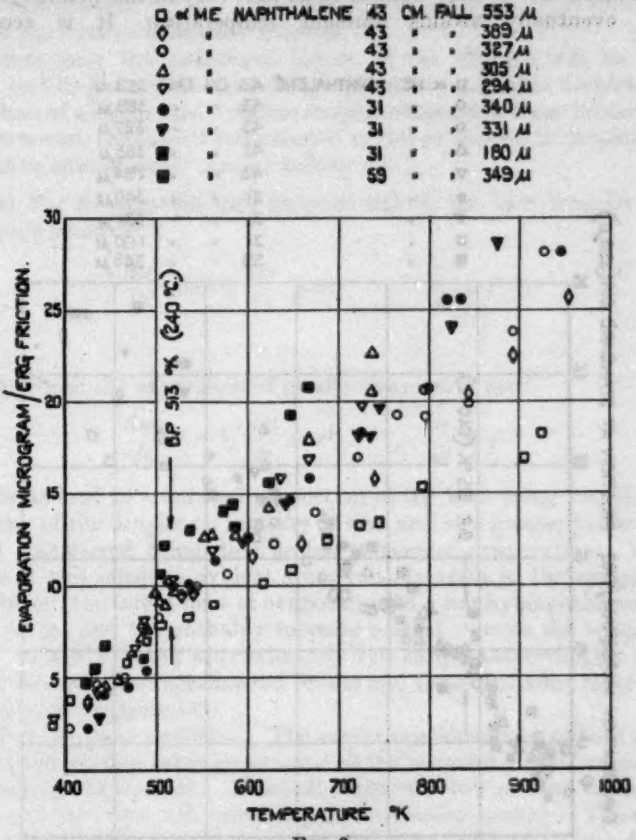


FIG. 6

DROPLET EVAPORATION PER UNIT FRICTION

also describes the mean velocity of the evaporating droplets in the furnace, then the rate of evaporation is approximately given by

$$\frac{dm}{dt} \propto \text{radius}^{1\cdot6-2\cdot0}$$

This experimentally determined relation is examined in the following sections.

Analysis of Results

The above relation for the variation of rate of evaporation with droplet radius is considerably different from that deduced earlier for the variation

of boundary-layer conductance. The latter indicates a flow of heat to the droplet varying approximately as radius $^{2\cdot3-2\cdot5}$ yet a rate of evaporation varying approximately as radius ^{5} is found.

The overall rate of heat transfer must also vary in this manner, since the vapour eventually attains ambient temperature. It is accordingly

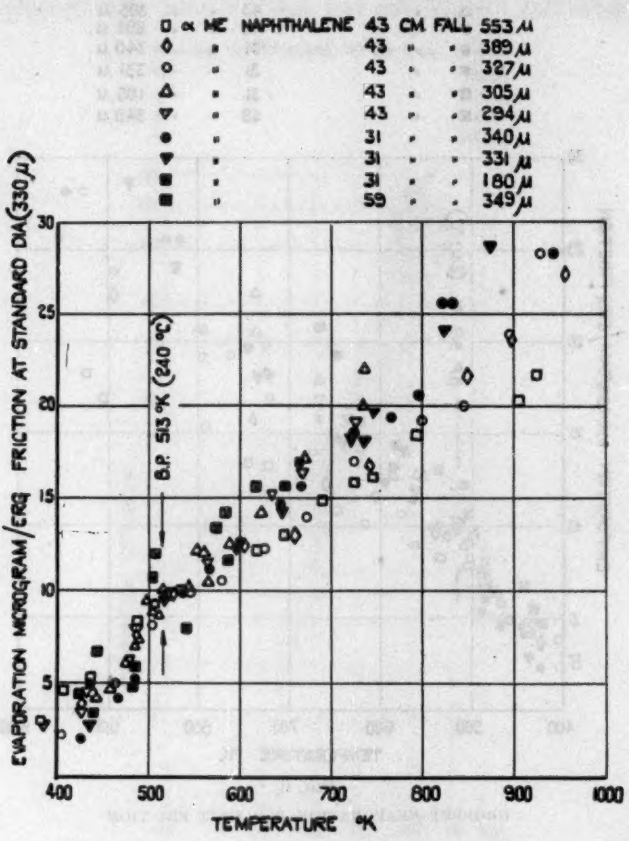


FIG. 7

DROPLET EVAPORATION PER UNIT FRICTION AT STANDARD DIAMETER

necessary to consider how the transfer of heat is distributed between the wake, the boundary layer, and the droplet surface.

Heat transfer in the droplet wake. The transfer of heat in the wake depends upon mixing processes, and since the areas involved are large compared with the droplets surface and boundary layer areas, this mixing may well provide effectively unlimited heat transfer, and variation with experimental conditions in the temperature of vapour leaving the boundary layer proper may well be masked.

Conduction of heat within the droplet. Of the heat which reaches the sur-

face of the droplet, some will be used in supplying latent heat of evaporation, and some will be conducted to the interior, to an extent depending upon the thermal conductivity of the droplet material. The latter will depend upon the surface area of the droplet. The heat reaching the surface of the droplet depends upon radius $^{2\cdot3-2\cdot5}$. Accordingly, a larger proportion will be conducted to the interior of smaller droplets.

Moreover, only the outermost layers of the droplet will be heated initially, and in given time a greater proportion of a smaller droplet will be heated than of a larger one. As the droplet evaporates these heated layers will be removed, the rate of reduction of radius of the larger droplets being greater than that of small ones as follows :—

(*a*) For evaporation rate proportional to the heat transfer to the droplet (minimum rate)

$$\frac{dm}{dt} \propto r^{2\cdot5}, \quad \frac{dm}{dr} \propto r^2, \quad \therefore \quad \frac{dr}{dt} \propto r^{0\cdot5},$$

whilst

(*b*) From the experimental results (maximum rate)

$$\frac{dm}{dt} \propto r^{4\cdot6}, \quad \frac{dm}{dr} \propto r^2, \quad \therefore \quad \frac{dr}{dt} \propto r^{2\cdot6}$$

These effects lead to a reduced proportion of the heat being transferred to the interior of the droplet on increase of size, and so a greater proportion of the heat transferred being used as latent heat of evaporation. The importance of this effect is evident from consideration of the quantities of heat involved, the latent heat of evaporation of α-methylnaphthalene being only 70 cal/g., and the enthalpy increase needed to raise the temperature from 20° to 240° C being approximately 110 cal/g. Accordingly, the discrepancy between the experimental results and those predicted theoretically can be reduced considerably.

The effect of vapour evolution. The earlier considerations of heat transfer to the droplet surface takes no account of the outward flow of vapour from the surface of the droplet. This will resist the flow of heat towards the droplet, and the effect will be analogous to effusion cooling. The effusion cooling effect [9] in the flow of gases through pipes is found to be a function of $\frac{V}{v}$, where V is the velocity of the coolant emerging normally from the walls and v the velocity of the gas parallel to them. It is reasonable to expect a similar relation to apply for the flow of vapour from the drop surface. Accordingly,

$$V \propto \frac{dm}{dt} \times \frac{1}{r^2}$$

For droplet velocity varying as $r^{1\cdot6}$ to $r^{2\cdot0}$

$$\frac{V}{v} \propto \frac{dm}{dt} \times \frac{1}{r^4} \qquad \left(\text{or } \frac{dm}{dt} \times \frac{1}{r^{3\cdot6}}\right)$$

Accordingly, it appears that provided $\frac{dm}{dt}$ does not vary as a power of

radius greater than about 4, there will be a greater reduction of the flow of heat to small droplets than to large ones.

It thus appears that there are two factors which lead to the evaporation rate varying with radius to a greater extent than may be predicted from simple theory, namely the conduction of heat to the interior of the drop, and the reduction of heat transfer to the surface, due to the outward flow of vapour. If the analogy used to estimate the effects of the latter is correct, the former is the more important. The overall effect due to the interaction of these two processes is not readily calculable. Since under given temperature conditions the rate at which heat passes to the interior of the droplet will be constant, variation in the transfer of heat to the drop will be magnified in the evaporation rate, the effects will augment each other, until there is a higher power of variation of evaporation rate with radius. Accordingly, it is considered that the experimental relations determined may be justified.

Variation of evaporation rate with temperature. In the light of the foregoing it is evident that the variation of evaporation rate with temperature is extremely complex. The retarding effect of the outward flow of vapour will lead to the rate of heat transfer increasing less rapidly than the temperature difference across the boundary layer, but as the effect of conduction of heat to the interior of the droplet is constant, evaporation per unit total heat transfer to the drop increases as the latter increases.

Moreover, the surface temperature of the droplet will attain such a value that that quantity of heat is transferred which is required to form vapour at the surface at such a rate that its removal by diffusion requires a partial pressure equal to the saturation pressure at that temperature.

At ambient temperatures considerably exceeding the boiling temperature, however, it may be anticipated that the surface approximately attains this value. The mean temperature of the droplet will be lower than the surface temperature, particularly at high rates of evaporation. Little error will arise if this effect is neglected in making a heat balance, however, as the heat content of the droplet residue is relatively small in these circumstances.

However, it is apparent that when the boundary layer breaks away from the drop its temperature varies between the drop surface temperature and the ambient temperature.

The vapour temperature must eventually attain the ambient value. Accordingly, transfer of heat in the wake must be included, and this heat transfer is better considered in terms of the frictional energy.

Fig. 8 shows a plot of calculated heat transfer per erg friction and ° K temperature difference. It may be seen that the results indicate an approximately equal proportionality between boundary-layer conductance per erg friction at temperatures exceeding by 200° C or more the boiling temperatures of the three hydrocarbons examined, but at lower temperatures the " conductance " increases sharply.

The former observation offers an empirical means of correlating the behaviour of the different hydrocarbons. Fig. 9 shows a plot of evaporation per unit friction at " standard " diameter, for the hydrocarbons used, with superposed lines *AA*, *BB*, and *CC*, showing the evaporation which would be obtained with " conductance " exactly proportional to friction, and it is evident that a good fit is obtained at air temperatures exceeding the boiling

temperatures by about 200° C, but that marked deviations occur at lower temperatures.

This relation is deduced for the total transfer of heat to the droplet and vapour. The quantity depends upon the mass of vapour actually formed and the temperature to which it is eventually heated. The mass of vapour formed depends upon the quantity of heat transferred to the

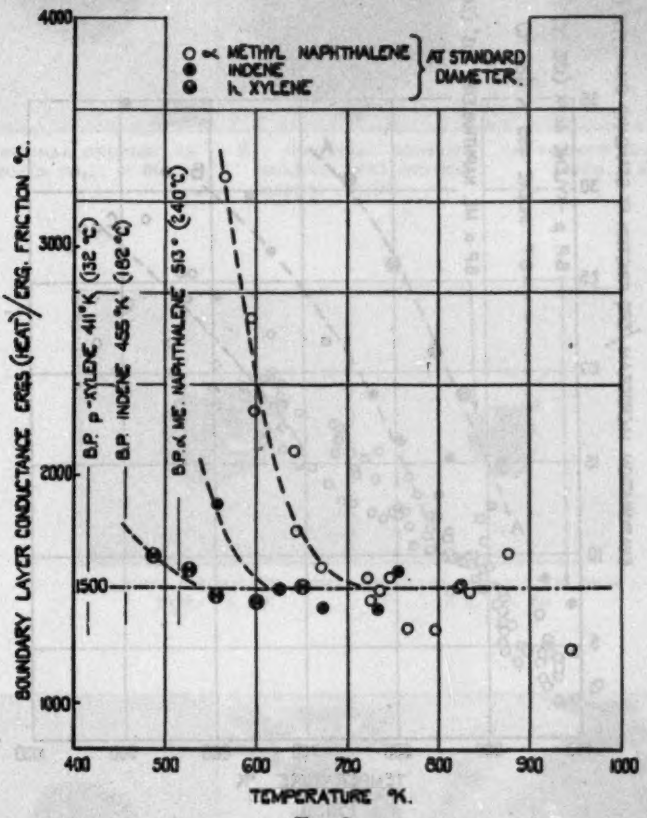


FIG. 8

BOUNDARY LAYER OF FALLING DROPLETS. CONDUCTANCE PER UNIT FRICTION

droplet, less that conducted to the interior. Accordingly, deviations apparent in Fig. 9 arise either from the effect of vapour evolution or conduction of heat to the interior of the drop influencing the heat available for evaporation, or from the droplet temperature having a value different from that assumed.

The former process would lead to an opposite variation of evaporation rate with temperature, and the deviation towards greater evaporation rates at lower temperatures is considerable and greater than would be anticipated from vapour evolution effects alone. Accordingly, there is some evidence in favour of the droplet temperature being significantly below the

boiling temperature until the ambient temperature is well in excess of it. In the absence of vapour evolution the surface temperature of α-methylnaphthalene droplets may be estimated by heat balance as being about

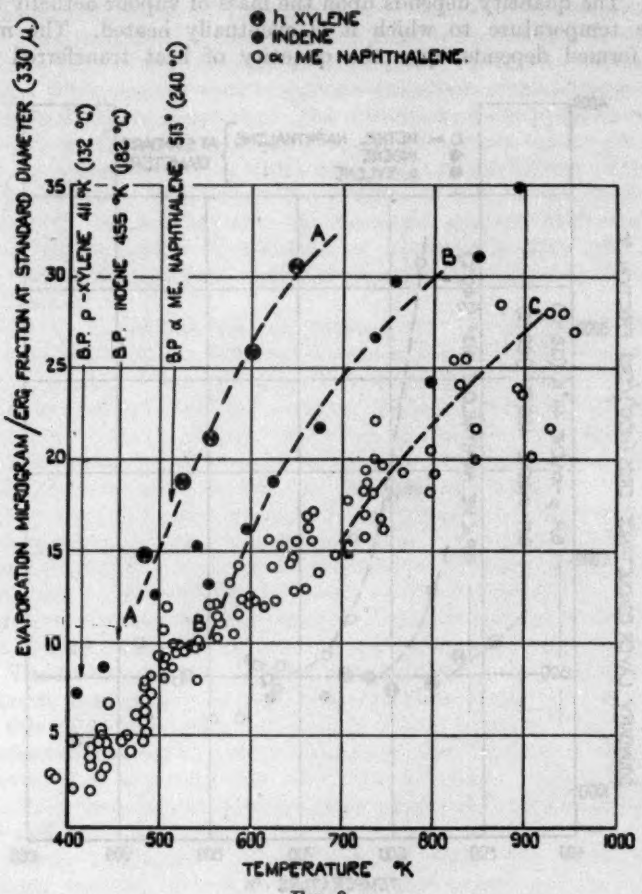


FIG. 9

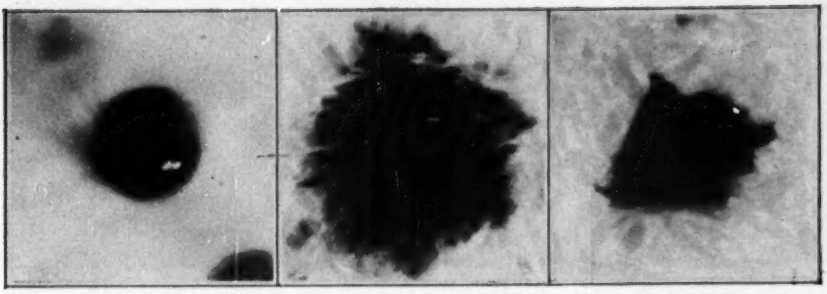
CORRELATION OF EVAPORATION OF FALLING DROPLETS AT STANDARD TEMPERATURE

460° K, when the ambient temperature is 513° K, the boiling temperature. This conclusion also accounts for the apparent increase in the ratio of conduction to friction shown in Fig. 8, at temperatures little above the boiling point.

EXPERIMENTS WITH RESIDUAL FUELS

Apparatus and Experimental Procedure

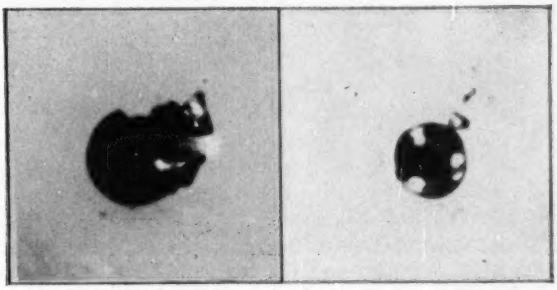
The apparatus used for the experiments with residual fuels was essentially similar to that described earlier. On account of the rapid rate of combustion of the drops, many experiments were carried out with a shorter



(*a*) ORIGINAL DROPLET ON SOLID CO_2. × 60.

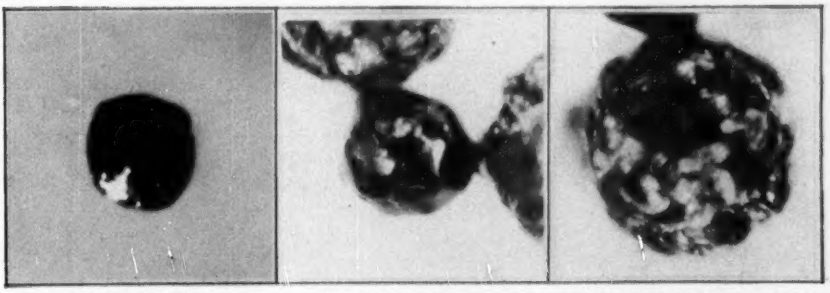
(*b*) ORIGINAL DROPLET SOAKED INTO FILTER-PAPER. × 36.

(*c*) VISCOUS LIQUID RESIDUE. × 60



(*d*) SOFT PITCH-LIKE RESIDUE. × 60

(*e*) HARD PITCH-LIKE RESIDUE. × 60



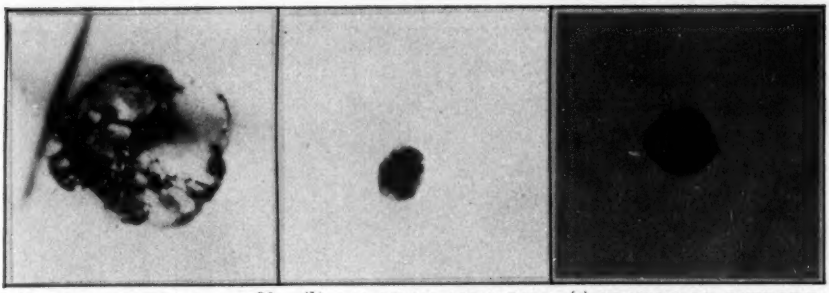
(*f*) SWOLLEN RESIDUE. × 60

(*g*) SWOLLEN RESIDUE. × 60

(*h*) FULLY SWOLLEN RESIDUE. × 60

PLATE I

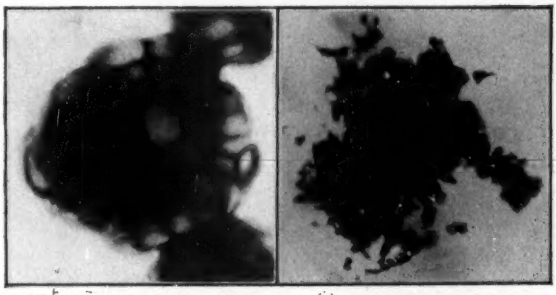
[*To face p.* 550.



(*a*) BURNT RESIDUE. × 60

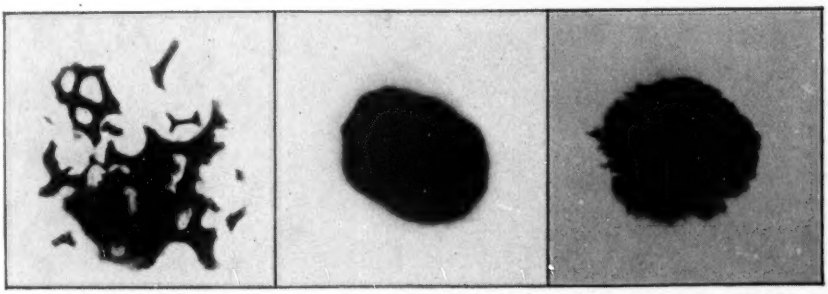
(*b*) COKE-LIKE HIGH-TEMPERATURE RESIDUE. × 60

(*c*) EROSION OF COKE-LIKE RESIDUE. × 60



(*d*) FULLY SWOLLEN RESIDUE. × 60
(By transmitted light)

(*e*) CRUSHED RESIDUE, FULLY SWOLLEN. × 25



(*f*) CRUSHED RESIDUE, PARTLY SWOLLEN. × 90
(By transmitted light)

(*g*) COKE-LIKE HIGH-TEMPERATURE RESIDUE. × 150
(By transmitted light)

(*h*) EROSION OF COKE-LIKE RESIDUE. × 150

PLATE II

furnace, so that the fall could be reduced to about 15 cm. Except for measurement of initial size, the droplets were collected upon filter-paper, rather than solid CO_2.

Fuels of 200, 1000, 3000, and 6000 Redwood seconds viscosity (100° F) were used. No quantitative measurements were made, but photomicrographs of residues were prepared, principally of the products of 6000 seconds fuel.

Experimental Results

Photomicrographs of the residues obtained from droplets of 6000 seconds fuel oil are shown in Plates I and II. Plate I (*a*) and I (*b*) show untreated droplets on solid CO_2 and soaked into filter-paper respectively. Plate I (*c*) shows a typical residue after passing through an atmosphere at approximately 400° C—an increase in viscosity is apparent as the residue has not soaked into the paper. Plates I (*d*) and I (*e*) show soft and hard pitch-like residues obtained at slightly higher temperatures. Plates I (*f*) and I (*g*) show early stages of the swelling process, and were obtained with furnace temperatures of approximately 600° C. Plate I(*h*) shows a fully swollen residue, now approximately double the original droplet diameter, obtained at approximately 700° C, and Plate II(*a*) shows the skeleton remaining after prolonged treatment at this temperature.

Slight flame only occurred at these temperatures, but at temperatures of 800° C and over luminous smoky combustion was observed. Plates II(*b*) and II(*c*) show the products obtained at these and higher temperatures, coke-like particles about one-half of the diameter of the original droplet, and fragile structures of eroded appearance. These residues could only be recovered using a short furnace length.

The remaining plates are concerned with the structure of the various particles. Plates II(*d*) and II(*e*) show a fully swollen particle after crushing and by transmitted light respectively. The complex bubble structure is shown by the latter, and the fragility of the walls by the former plate. Plate II(*f*) shows a crushed partly swollen particle by transmitted light. The thick junctions of the cell-wall joints are evident. Plates II(*g*) and II(*h*) show a coke particle and an eroded particle by transmitted light. The dense structure is apparent.

Residues of these types were obtained from droplets of all the residual fuels used, though both the swollen and coke-like residues were proportionately smaller. The most important observation is considered, however, to be that no swollen particles could be obtained from droplets of original diameter greater than about 280 μ, as it may be used to deduce a possible explanation of the experimental findings.

The results of the experiments with pure hydrocarbons, which showed the rate of evaporation per unit length to be proportional to the mass of the droplet, indicate that the swelling occurs only at low rates of evaporation, and accordingly, only under those conditions when the interior of the drop may be substantially heated before evaporation is effectively complete. These results further suggest that with droplets of diameter ~300 μ the rate of evaporation was insufficient at ambient temperatures exceeding the boiling temperature by less than 400° C. to prevent sufficient heat being conducted to the interior of the droplet to "saturate" its heat capacity. Accordingly, at ambient temperatures up to about 800° C it is likely that

the temperature of whole of the residue of a heavy fuel droplet of diameter $<300\ \mu$ is probably close to the normal bubble point. Lower temperatures only would be attained in larger droplets. Thus if cracking, through gas evolution, is responsible for the swelling of residual fuel droplets under the experimental conditions, the dependence of the latter upon droplet size and persistance to the observed temperature are accountable. The change in character of the residue at higher temperatures would possibly indicate that the residue experiences a lower mean temperature during its life. Experimental results for the pure hydrocarbons are not available for these conditions, however, so this is not certain, and, moreover, no reason can be advanced on the basis of the evidence available for the formation of the coke-like residues. The reasons advanced for the swelling are valid, however, granted that cracking can occur under the experimental conditions, which is considered likely, though some doubt must exist as the chemical constitution of the fuels is unknown.

Discussion of Results

The experiments described here are essentially preliminary in character, being designed to obtain information on the behaviour of fuel droplets under conditions as close to those obtaining in gas-turbine combustion systems as is practicable. They are justified, as they have demonstrated that the relations $(dm/dt)a\gamma^{2.3-2.5}$ deduced for slow evaporation rates is subject to severe modification when small droplets are evaporated in atmospheres at temperatures well in excess of their boiling temperatures. Though no quantitative measurements of burning rate have been made, it may be inferred that the substitution of a flame front for a hot ambient atmosphere will have no significant change on the mechanism.

In any application of these results it must be remembered that they relate only to droplets moving at their terminal velocities, a condition which may not always be attained in practice. Moreover, they are not directly applicable to complete evaporation. The reason suggested for the departure of the evaporation rate from that predicted from heat-transfer condition being that the interior of the larger drops is heated to a less extent than is the case with smaller droplets, completion of their evaporation will accordingly require a relatively longer time, and the experimental relation deduced for partial evaporation will not be directly applicable to total evaporation.

The quantitative results are, moreover, of limited accuracy only, and the analysis is mainly qualitative. For scientific purposes a more exact treatment in both respects is necessary. For practical purposes, however, the indication that the attainment of finer atomization will give less advantage than that predicted from theory is, however, significant. Moreover, the results suggest that increase of the aerodynamic forces acting upon the droplets by means of organized turbulence will be of advantage. Since it may be deduced from the general heat-transfer mechanism that the rate of evaporation will change when the droplet inflames, information of a limited accuracy only is necessary, in the absence of detailed information on the delay before ignition.

The results for heavy fuels indicate that swollen particles of low density may be obtained when droplets are evaporated in air at 700° to 800° C.

Since these can move only slowly relative to the air, the completion of their combustion may be difficult, and it is considered that these conditions should be avoided in the design of combustion systems. Considerably more information is needed, however, in order to account for the phenomena with certainty.

Conclusions

The experimental results indicate that the rate of evaporation of hydrocarbon droplets in atmospheres at temperatures considerably above their boiling temperature depends mainly upon heat transfer to the droplets, but that the rate deduced from simple theory is modified by the outward flow of vapour from the droplet surface and the conduction of heat to the interior, so that the actual rate may be described by the equation

$$\frac{dm}{dt} \propto r^{1.6}$$

for droplets falling at their terminal velocities.

It is concluded that in gas-turbine practice less advantage will be obtained by securing fine atomization than is to be expected from simple heat-transfer theory alone.

When the ambient temperature exceeds the boiling temperature by >200° C, the latter value may be assumed for the surface temperature. At lower ambient temperatures, a lower surface temperature is attained, apparently that which corresponds to the vapour pressure needed for the removal by diffusion of that quantity of vapour whose formation is permitted by the heat transfer.

The results for kerosine indicate evaporation at a rate as for a pure hydrocarbon boiling at the normal bubble point. Some fractionation or cracking occurred with the gas oil.

Droplets of residual fuel tend to swell at temperatures of approximately 600° to 800° C, but at higher ambient temperatures small coke-like residues are obtained.

Acknowledgments

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THE FLOW PATTERN OF GAS TURBINE COMBUSTION

By F. H. GARNER, O.B.E. * (Fellow), and H. A. CHEETHAM †

INTRODUCTION

THE study of combustion problems in the laboratory depends on the closeness with which large-scale behaviour can be simulated in small-scale laboratory apparatus.

Experimental work was first conducted which led to the design of a gas-turbine combustion chamber to atomize and burn about 50 cc of fuel per hour. Its performance characteristics with rates of air flow from 5 to 40 g/minute were investigated with various flame stabilizers. The flame temperatures and flame stabilities of a series of fuels—propane, petroleum ether, *iso*-octane, heptane, and benzene—have been measured over a range of pressures from 100 mm to atmospheric.

The flame temperatures with the atomized fuels were about 500° C lower than the theoretical temperatures calculated for the air–fuel ratios used with the pre-vaporized fuels. These lower temperatures appear to be primarily due to the fact that they are average temperatures across the combustion chamber and not the higher temperatures. It was therefore concluded that the main factors determining the stability limit are the flow pattern and the axial air velocity in the combustion.

This paper describes the investigation of these factors.

APPARATUS

The apparatus is shown schematically in Fig. 1. Three supplies of air, that is atomizing air, primary air, and cooling air, were taken from the same compressor and separately metered to the apparatus. The fuel supply was from a constant-head device and was metered by a rotameter, the temperature of which was maintained constant.

The flame tube could be operated at atmospheric pressure or under vacuum. When partial vacuum was used, it was controlled by a throttling valve in the line to the pump, and when adjusted to the desired value it was held constant by a manostat operating a solenoid valve which adjusted the leak into the system.

The atomizer unit, Fig. 2, was an air-blast type which could atomize fuel at a rate of up to 2 cc/minute using air at a pressure of up to 30 p.s.i. at a rate of up to 1·8 g/minute. To prevent irregularities in fuel flow due to vapour lock, the unit was water-cooled and the fuel rate was controlled by a needle-valve fitting at the end of the nozzle. With the valve in this position the pressure in the flame tube could be lowered while maintaining a positive pressure in the fuel line. The needle valve was adjusted by a micrometer thread on the spindle and a reduction gear, and one turn of the control knob moved the valve 0·0018 inch.

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The bell-mouth shape at the exit of the nozzle eliminated fuel drooling from the tip, a trouble which was experienced in earlier designs of the unit.

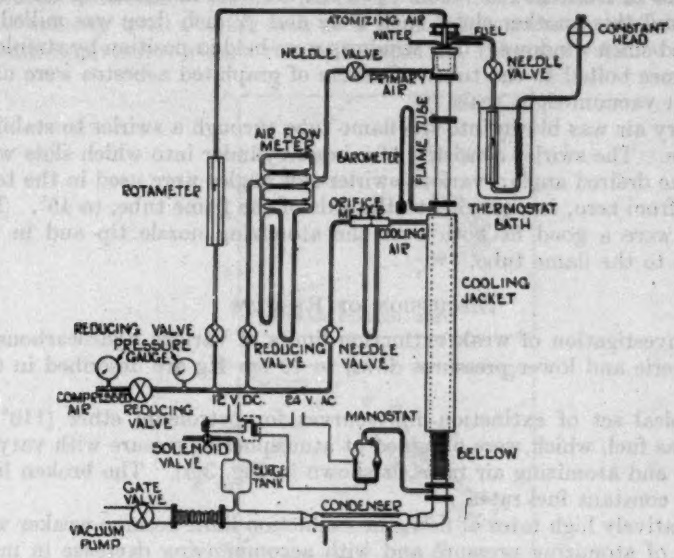

FIG. 1

DIAGRAM OF APPARATUS

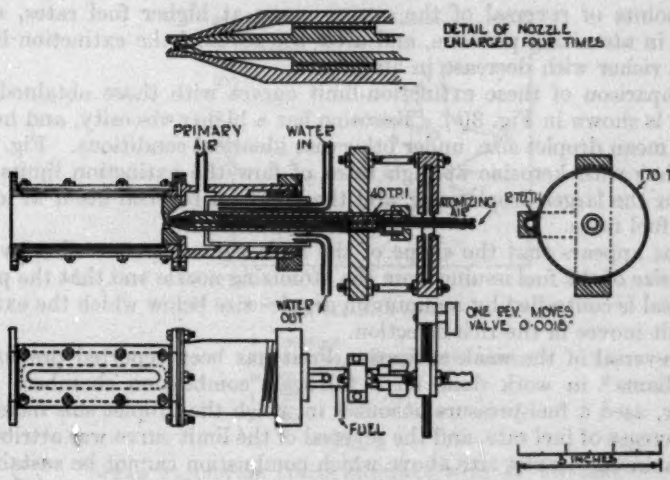

FIG. 2

ATOMIZER UNIT AND 3-INCH SECTION OF FLAME TUBE

The droplet size produced by this atomizer was measured with the impression method on magnesium oxide [1] and gave spray S.M.D.s of the order of 25 microns.

The flame tube was in two sections, one 3 inches long, Fig. 2, and the other 6 inches long. They were 1-inch inside diameter and were machined from a bar of Nimonic 80. Slots $\frac{5}{16}$ inch wide were milled along the tube, and around this another slot $\frac{1}{2}$ inch wide and $\frac{3}{32}$ inch deep was milled to hold fused-silica windows. The windows were held in position by stainless-steel frames bolted to the tube. Gaskets of graphited asbestos were used to obtain vacuum-tight seals.

Primary air was blown into the flame tube through a swirler to stabilize the flame. The swirler consisted of a brass cylinder into which slots were cut at the desired angle; various swirler-slot angles were used in the tests ranging from zero, *i.e.*, parallel to the axis of the flame tube, to 45°. The swirlers were a good fit both over the atomizing nozzle tip and in the entrance to the flame tube.

Discussion of Results

The investigation of weak extinction limits of various hydrocarbons at atmospheric and lower pressures down to 10 cm Hg are described in this paper.

A typical set of extinction-limit curves for petroleum ether (110° to 120° C) as fuel, which were obtained at atmospheric pressure with varying primary and atomizing air rates, is shown in Fig. 3(*a*). The broken lines indicate constant fuel rates.

At relatively high rates of flow, the extinction limit became weaker with increase of atomizing pressure and with accompanying decrease in mean droplet size. The extinction limit also became weaker with decrease in air rate and hence also in fuel rate, and this again reduced the mean droplet size.

The points of reversal of the curves occur at higher fuel rates, with increase in atomizing pressure, and after the reversal the extinction limit becomes richer with decrease in air rate.

A comparison of these extinction-limit curves with those obtained for kerosine is shown in Fig. 3(*b*). Kerosine has a higher viscosity, and hence a larger mean droplet size, under otherwise identical conditions. Fig. 3(*b*) shows that with kerosine at high rates of flow the extinction limits are richer for the larger droplet size, and the points of reversal occur at lower air and fuel rates.

It thus appears that the shape of the limit curves is controlled by the droplet size of the fuel issuing from the atomizing nozzle and that the point of reversal is controlled by a minimum droplet size below which the extinction limit moves in the rich direction.

The reversal of the weak extinction limit has been reported previously by Williams [2] in work done on a full-scale combustion chamber. He, however, used a fuel-pressure atomizer in which the droplet size *increased* with decrease of fuel rate, and the reversal of the limit curve was attributed to a maximum droplet size above which combustion cannot be sustained; the limit moves in the rich direction along a line of constant fuel flow.

The effect of droplet size was, however, not of prime importance in controlling the shape of the stability curves, as typical weak limit curves (Fig. 3(*c*)) were obtained using gaseous propane as fuel.

Investigation of the axial air velocity down the flame tube was made, using a velometer with the tip of the velometer tube held a distance of

$\frac{5}{16}$ inch from the entrance to the flame tube. In Fig. 4 the velocity of the atomizing air alone, at various atomizing air pressures, is shown on the abscissa. Increase of primary air causes an initial reduction in the overall axial velocity until a point such as B is reached on the curve (for 20 p.s.i. atomizing pressure) when a reversal occurs and the axial velocity increases

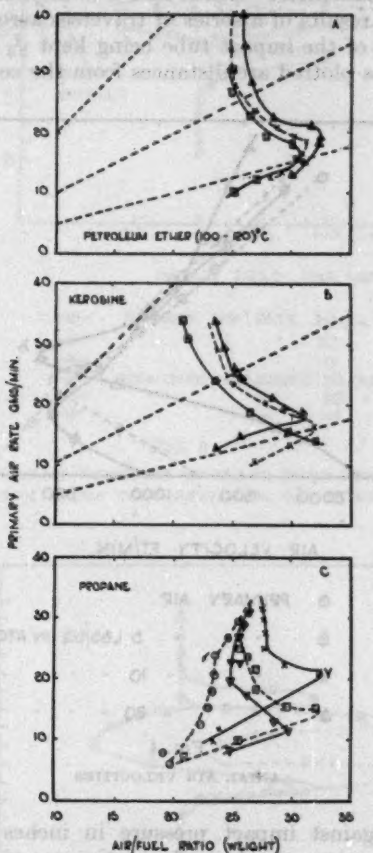

FIG. 3

WEAK EXTINCTION LIMITS OBTAINED WITH 45° SWIRLER
A. Petroleum Ether. B. Kerosene. C. Propane.

with increase in primary air rate. There is a marked similarity between the shape of the curves obtained in this experiment and the curves of extinction limits given previously. The significance of this will be discussed after the next series of experiments has been described.

Although average axial air velocities could be obtained using the velometer, accurate measurements at particular points were not obtainable by the use of this instrument. A small impact tube, made from hypodermic tubing, was satisfactory, and was traversed across a diameter of the flame tube. The impact pressure was measured on a two-liquid (benzoyl alcohol–calcium chloride) manometer [3] which had a multiplication factor of 20.

Fig. 5 shows the results of a series of traverses across a diameter of the flame tube, the tip of the impact tube being kept $\frac{7}{32}$ inch away from the swirler. The values plotted are distances from the centre line of the tube

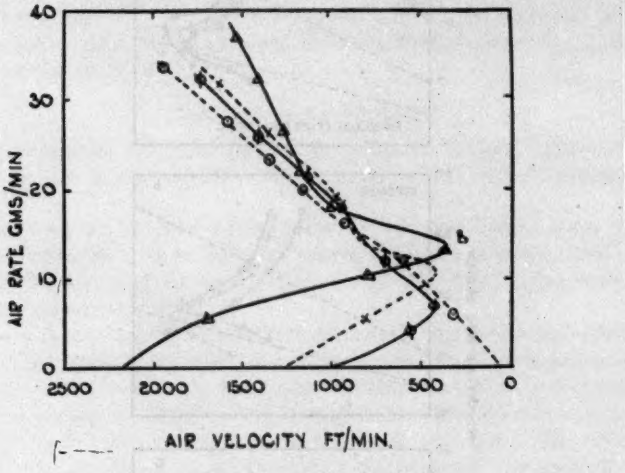

FIG. 4
AXIAL AIR VELOCITIES

in $\frac{1}{16}$-inch units against impact pressure in inches of water. Positive pressures are above atmospheric, and negative pressures below. The outside diameter of the swirler and the atomizing nozzle are shown on the graph.

That the negative pressures obtained with only primary air flowing are due to the swirl imparted to it is shown in Fig. 6, which gives results of traverses across a swirler with 45° slots and one with 0° slots, *i.e.* slots cut parallel to the axis. This graph also shows that the maximum forward velocity is considerably less when swirl is imparted to the air. This would be expected, since there is then a velocity component at right angles to the axis of the combustion chamber.

Fig. 7 shows the results of the pressure traverses when both atomizing and primary air are flowing. The swirl imparted to the primary air

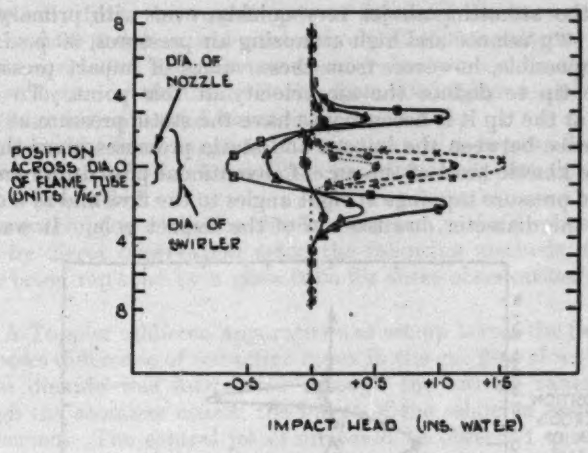

FIG. 5

IMPACT PRESSURES ACROSS DIAMETER OF FLAME TUBE PITOT TUBE $\frac{7}{32}$ INCH FROM FLAME TUBE ENTRANCE, 45° SWIRLER

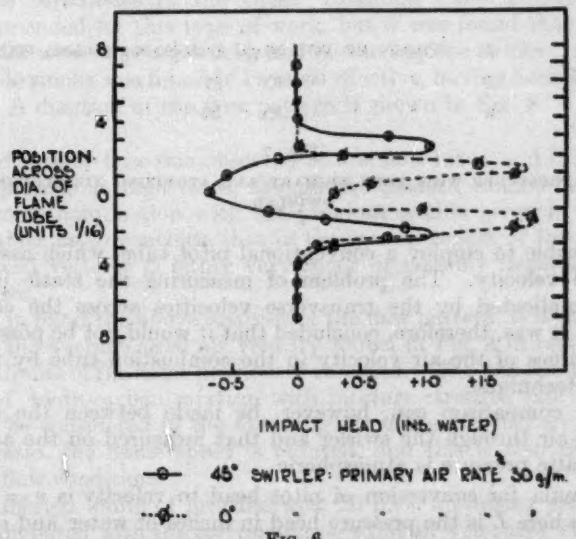

FIG. 6

IMPACT PRESSURES WITH 45° AND 0° SWIRLER

destroys the atomizing air jet very quickly, even with primary air rates as low as 10 g/minute and high atomizing air pressures, 30 p.s.i.

It is impossible, however, from these values of impact pressure at the pitot-tube tip to deduce the air velocity at this point. To obtain air velocities at the tip it is necessary to have the static pressure at this point, the difference between the impact and static pressures gives the pressure due to the kinetic head of the air. Conventional pitot tubes are designed with static-pressure tappings at right angles to the flow and at a distance of six times the diameter downstream of the impact hole. It was not con-

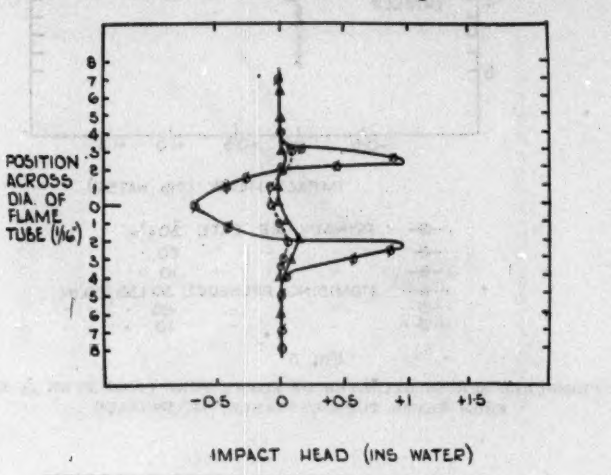
POSITION ACROSS DIA. OF FLAME TUBE (1/16")
8 7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 8
-0·5 0 +0·5 +1 +1·5
IMPACT HEAD (INS WATER)
ϕ PRIMARY AIR RATE 30 g/m: 10 LBS/SQ.IN ATOMISING PRESS.
⊙ · · 10 · 10 · · · ·
▲ · · · 10 · 30 · · · ·

FIG. 7

IMPACT PRESSURES WITH BOTH PRIMARY AND ATOMIZING AIR FLOWING, 45° SWIRLER

sidered possible to employ a conventional pitot tube, which assumes constant axial velocity. The problem of measuring the static pressure is further complicated by the transverse velocities across the combustion chamber. It was, therefore, concluded that it would not be possible to get absolute values of the air velocity in the combustion tube by the use of pitot-tube technique.

A rough comparison can, however, be made between the calculated velocity of air through the swirler and that measured on the assumption that the static pressure is atmospheric.

The formula for conversion of pitot head to velocity is $v = 18{\cdot}3\sqrt{L/\rho}$ ft/second, where L is the pressure head in inches of water and ρ is the air density; hence $v = 3900\sqrt{L}$ under atmospheric conditions. The maximum impact head at a primary air flow rate of 20 g/minute from Fig. 5 is 0·45 inch, which gives a velocity of 2600 ft/minute. Calculation of the

entrance velocity from the volume rate of flow and the known total slot area in the swirler (0·019 sq. in.) gives a figure of 4500 ft/minute. It may, therefore, be concluded that the transverse velocity must be considerable to effect a reduction of the total velocity from 4500 ft/minute to the value of 2600 ft/minute in an axial direction.

It has previously been suggested [4] that there is a reverse flow in the centre of the vortex of a swirler, and the above data support this although they are not conclusive.

A further attempt to elucidate the flow pattern in the combustion tube was made by direct observation using the following methods, the metal flame tube being replaced by a glass tube for these observations :—

(1) A Toppler schlieren apparatus was set up across the flame tube; this shows difference of refractive index in the gas flow along the tube. Carbon dioxide was introduced through the swirler vanes and air through the atomizer nozzle, the image of the schlieren being focused on a screen. The central jet of air could be observed quite clearly; when the primary air, in this case carbon dioxide, was passed, the pattern of the flow at low rates could be observed, but when the rate was increased the turbulence in the tube was so intense that no definite pattern could be observed.

(2) Smoke introduced through the swirler was also used in an attempt to define the flow pattern. It was found that a flat beam ($\frac{1}{32}$ inch thick) of very intense light shining through a diameter of the flame tube showed up a distinct flow pattern at low rates of flow. At high rates, however, no definite pattern could be distinguished owing to the intense turbulence in the tube. Titanium oxide smoke has been recommended for this type of work, but it was found that the smoke particles were large and sticky and blocked up the swirler; ammonium chloride smoke was found to be more effective, having a smaller particle size. A diagram of the flow pattern is shown in Fig. 8.

A region of reverse flow was observed at low flow rates, and it is probable that this persists at high rates, though the pattern cannot be observed. This, taken in conjunction with the previous results given in Figs. 5, 6, and 7, enables us to conclude that in the central region of the vortex the forward axial velocity is either very small or possibly negative, *i.e.*, the flow reverses.

Bearing in mind the above analysis of the flow pattern, it is possible now to discuss the average axial air velocity shown in Fig. 4 in relation to the extinction limits of the flame previously obtained. The variation of burning velocity of hydrocarbon mixture with mixture strength (air : fuel ratio) must also be considered in the following discussion. With an increase of air : fuel ratio, the flame speed is reduced, and this is also obtained in turbulent-flow conditions.

The extinction limits of propane with 20 p.s.i. atomizing pressure, Fig. 3(*c*), are compared with the corresponding axial air velocities with 20 p.s.i. atomising pressure (Fig. 4). At low rates of primary air flow, the extinction limit occurs at relatively low air : fuel ratios; increasing the air rate weakens the limit to point Y, Fig. 3 (*c*). The corresponding air velocities, Fig. 4,

are high at low rates of primary air flow, decreasing with increase in air rate to point B. It is only possible to obtain a stable flame at high axial velocities if the mixture strength is moved towards stoichiometric values, *i.e.*, richer. Decreasing the axial air velocity allows a stable flame to be maintained at greater air : fuel ratios than is possible if the axial velocity is high. After point B on Fig. 4 the velocity increases with increase of air rate; also on Fig. 3(*c*) after point Y the air : fuel ratio at which stable burning is possible decreases with increased air rate. If atomizing pressure decreases, the primary air rate at which reversal of the extinction curves occurs also decreases; simultaneously the air rate at which reversal of the axial velocity occurs decreases; these are again related by the dependence of burning velocity on air : fuel ratio. Increase of atomizing pressure has a similar effect.

The air rates at the points of reversal are not, however, the same in Figs. 3(*c*) and 4, as the extinction curve with 20 p.s.i. atomizing pressure reverses at an air rate of 20 g/minute (point Y), whereas the corresponding

FIG. 8

DIAGRAM OF FLOW PATTERN

velocity curve reverses at 14 g/minute (point B). It was seen from the detailed plots of the air flow pattern, Fig. 7, that the shape of the jet of atomizing air (same as the spray shape) was destroyed by the primary air. If the stages of the destruction of this spray are followed, at first, with only atomizing air flowing, there is a jet-shaped spray; then increase of primary air gradually shortens the distance from the nozzle at which a spray can be defined, *i.e.*, the greater the distance from the nozzle the less primary air is required for destruction of the spray and the reversal of the velocity. The curves on Fig. 4 were obtained with the velometer at $\frac{5}{16}$ inch from the nozzle, whereas the flame stabilizes at approximately $\frac{1}{8}$ to $\frac{3}{16}$ inch from the nozzle. It thus seems likely that the difference between the rates of flow at corresponding reversal points in the two figures can be explained on this basis.

The above discussion applies to the extinction limit curve of a gaseous fuel (propane) with air. Consideration of the extinction curves for petroleum ether and kerosine shows that the same reasoning can be applied, even although an atomized and not a gaseous fuel is being burnt.

It is thus possible to explain why flames cannot be stabilized at very low flow rates. Until a critical amount of primary air is flowing, the resultant axial velocity is not low enough for a flame to stabilize even at mixtures where the flame speed is high, *i.e.*, richer mixtures.

It is not suggested, however, that there is an exact equivalence between the flame speed of the mixture and the velocities shown in Fig. 4. The maximum laminar burning velocity of propane has been reported [5] as 50 cm/second. Intense turbulence present in the flame tube would increase this maximum, probably by a factor of about 4, to approximately 350 ft/minute. The minimum overall axial velocity shown in Fig. 4 is also 350 ft/minute, but on the other hand at the extinction limit, the burning velocity is very considerably lower than the maximum by a factor of at least 10, and then the inequality becomes obvious. The flame appears in fact to be anchored in the region of very low or reverse flows shown in Fig. 8.

Comparison of Stability Limit with Inflammability Limit

Fig. 9 shows the stability limits of heptane at atmospheric pressure and under reduced pressure, and similar curves were obtained for propane, benzene, and *iso*-octane.

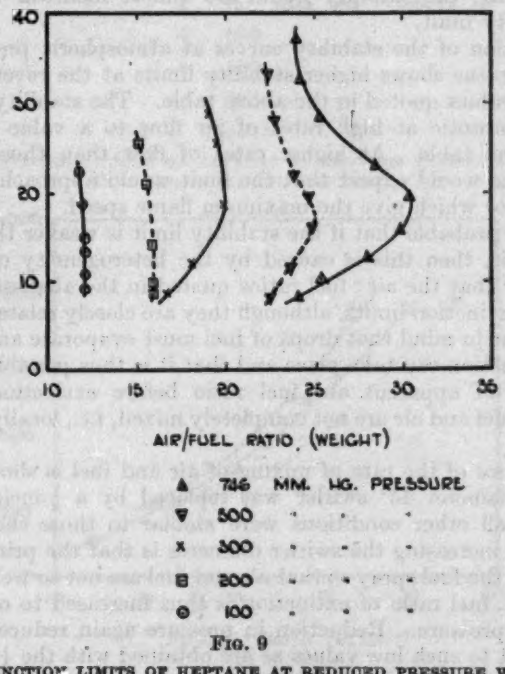

FIG. 9

WEAK EXTINCTION LIMITS OF HEPTANE AT REDUCED PRESSURE WITH 45° SWIRLER ¼ INCH DIAMETER

The values for the weak inflammability limits of the hydrocarbons at atmospheric pressure are shown in Table I.

There is a marked discrepancy between the limits shown in Table I. The values in column (1) are from Jost,[6] and those in column (2) were determined by Egerton and Powling [7]; these results were obtained in a static

TABLE I

Hydrocarbon	Weak inflammability limit			Stoichiometric air : fuel	Max burning vel., cm/second
	(1)	(2)	(3)	(4)	(5)
Benzene . .	25·8	—	—	13·2	56·4
iso-Octane . .	—	21·7	—	15·05	42·4
Heptane . .	28·5	22·6	—	15·1	47
Propane . .	27·0	25·2	30·6	15·6	50·2

apparatus. Column (3) shows a recent result given by Powling [8] by extrapolation of burning velocity obtained by the " flat-flame " technique back to zero velocity. Column (5) gives values of laminar burning velocity determined by Ashforth.[5]

Results obtained by Heron and Baldwin [9] show that with pre-vaporized fuel or gaseous fuel injected into a swirling air stream to ensure almost perfect mixing, the stability limits are almost identical with the static inflammability limit.

Consideration of the stability curves at atmospheric pressure obtained in this apparatus shows higher stability limits at the reversal point than the highest values quoted in the above table. The stability limit tends to become asymptotic at high rates of air flow to a value between those quoted in the table. At higher rates of flow than those used in this apparatus one would expect that the limit would approach stoichiometric air : fuel ratios which give the maximum flame speed.

It appears probable that if the stability limit is weaker than the inflammability limit, then this is caused by the heterogeneity of the mixture. It is unlikely that the air : fuel ratios quoted in the abscissa of the curves control the extinction limits, although they are closely related to them. It must be borne in mind that drops of fuel must evaporate and mix with air before combustion can take place and that it is thus possible to have very large values of apparent air : fuel ratio before extinction takes place, because the fuel and air are not completely mixed, *i.e.*, locally rich mixtures can occur.

The influence of the rate of mixing of air and fuel is shown in Fig. 10; the $\frac{1}{4}$-inch diameter 45° swirler was replaced by a $\frac{1}{2}$-inch diameter 45° swirler, but all other conditions were similar to those shown in Fig. 9. The effect of increasing the swirler diameter is that the primary air is not directed into the fuel spray so that air and fuel are not so well mixed. The apparent air : fuel ratio of extinction is thus increased to over 90 to 1 at atmospheric pressure. Reduction in pressure again reduces the stability limit, but not to such low values as are obtained with the $\frac{1}{4}$-inch diameter swirler.

Extinction Limits and Reduction in Pressure

Reduced pressure in the combustion chamber reduces the maximum air : fuel ratio at which combustion is possible for all the hydrocarbons used; this is illustrated in Fig. 9.

The results obtained for heptane, *iso*-octane, benzene, and propane have

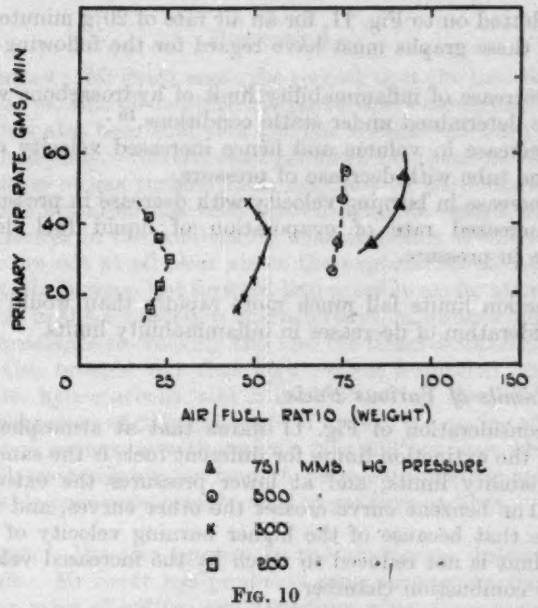

FIG. 10

WEAK EXTINCTION LIMITS OF HEPTANE AT REDUCED PRESSURE WITH 45° SWIRLER ½ INCH DIAMETER

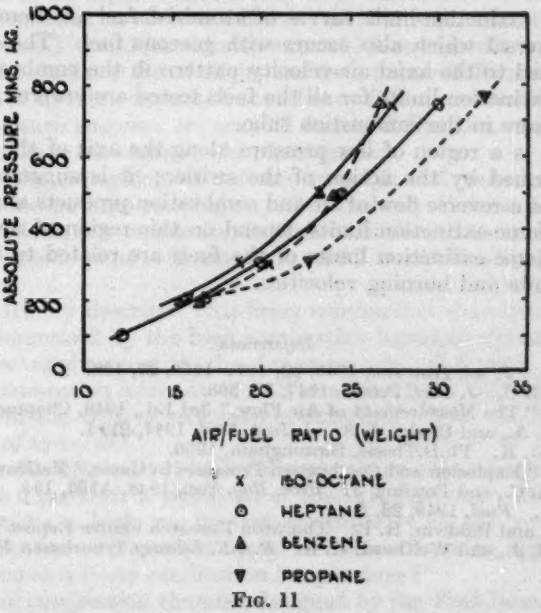

FIG. 11

WEAK EXTINCTION LIMITS OF ISO-OCTANE, HEPTANE, BENZENE AND PROPANE WITH VARIATION IN PRESSURE

been cross plotted on to Fig. 11, for an air rate of 20/g minute. An interpretation of these graphs must have regard for the following factors :—

(1) Decrease of inflammability limit of hydrocarbons with reduced pressure determined under static conditions.[10]

(2) Increase in volume and hence increased velocity of the air in the flame tube with decrease of pressure.

(3) Increase in burning velocity with decrease in pressure.[5]

(4) Increased rate of evaporation of liquid fuel droplets with decrease in pressure.

The extinction limits fall much more rapidly than would be expected from a consideration of decreases in inflammability limits.

Extinction Limits of Various Fuels

Further consideration of Fig. 11 shows that at atmospheric pressure, the order of the extinction limits for different fuels is the same as that for the inflammability limits, and at lower pressures the extinction limits converge. The benzene curve crosses the other curves, and the explanation may be that because of the higher burning velocity of benzene the extinction limit is not reduced so much by the increased velocity of flow through the combustion chamber.

Conclusions

(1) Weak extinction-limit curves of atomized fuel are found to have a point of reversal which also occurs with gaseous fuel. These curves are closely related to the axial air-velocity pattern in the combustion tube.

(2) The extinction limits for all the fuels tested are lowered, with reduction in pressure in the combustion tube.

(3) There is a region of low pressure along the axis of the combustion chamber formed by the action of the swirler; it is suggested that this region causes a reverse flow of air and combustion products along the axis.

(4) The flame-extinction limits depend on this region of reverse flow.

(5) The flame-extinction limits of the fuels are related to their inflammability limits and burning velocities.

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Discussion

The Chairman: Mr Scott made the remark that the best fuel of all was found to be the paraffin oil on which the gas turbine was originally developed, although it has also been said that the gas turbine can burn any type of fuel, even candle ends. Nevertheless, although the chemical characteristics and composition of gas turbine fuels may not be particularly important when adequate attention has been concentrated on design, there are important differences in the combustion characteristics of different types of fuel, and we are not at all clear about the explanation of the differences. For example, Mr Dawson put forward two possible explanations as regards the differences in the combustion characteristics of toluene and *iso*-octane, namely the resistance to cracking and also the latent-heat effect. The first two papers also brought out that high carbon formation occurred when using aromatic hydrocarbons, and it is obvious that the information concerning the behaviour of different types of fuels in the engine will be of very great interest in connexion with design; it is still not clear whether all the middle distillates available for modern petroleum-refining methods (even when of suitable pour point) can be used as gas turbine fuels.

I. G. Bowen: My own interest in this discussion lies largely on the industrial side. Mr Scott has produced some interesting curves showing the deposition rates of sodium and vanadium when these are added to gas oil, and he suggests from the experimental results that sodium is about twice as bad in its deposition tendency as is vanadium. In the paper he has pointed out that, as soon as a heavy fuel is burned, an inhibiting effect is obtained, and I would like him to expand his statements with regard to that. A very similar state of affairs has been found at Thornton, where it was attempted to catch deposits from a heavy fuel oil combustion chamber, but without much success; we are still finding difficulties, and it would be interesting to have his views on the phenomenon.

Secondly, the deposition of sodium, vanadyl, and vanadate, has been verified in some turbines running on heavy fuel oil; the results apparently agree with laboratory experience, in that corrosion tends to be inhibited. Mr Scott has made some reference to it, and I would like him to elaborate on that also.

Then Mr Hurley described coal-firing combustion chambers, and I was very much impressed by the high combustion intensity obtained with the Westinghouse appliance with the Lummus type of burner. They have attained a combustion intensity of half a million B.Th.U/ft^{3}hr. I did not hear details of the type of atomization obtained. Does Mr Hurley know the fineness of the coal?

I am quite familiar with the NGTE vortex type of combustion chamber. I believe the diluent air is admitted at the exit from the vortex chamber, and one obtains a high combustion temperature in the vortex proper. Will the same sort of treatment apply in the coal-burning appliance, or is the vortex run at a lower combustion temperature?

The type of combustion chamber designed by the Fuel Research Station depends on a coating of slag on the bricks. Has experience been obtained with the refractories to show whether or not any damage results from the

shut-down of these combustion chambers? If the bricks are subjected to operation under steady conditions one assumes that their quality will be good enough to withstand service conditions, but I imagine that some glaze will be formed when the combustion chambers are shut down, with consequent cracking and flaking of the surfaces of the bricks.

The paper by Garner and Cheetham contains a very great deal of information. A large number of experiments was made with what amounts to different aerodynamic devices. At Thornton we have very much the same sort of thing in mind in planning a programme for the study of different combustion-chamber configurations. What sort of combustion was obtained when the various changes were made? In a research-minded attitude towards this job I am wondering whether combustion suffered at times and whether that would have an invalidating effect on any of the results.

Mr Scott: With regard to the point raised by Dr Bowen concerning deposits on turbine blades from sodium and vanadium, it was found that sodium gave twice as heavy a deposit as vanadium. I think that can be accounted for by the formation of sodium sulphate on the blades, as opposed to the deposition of vanadium pentoxide. It may be quite an advantage to have some sodium sulphate present when it comes to the practical running of gas turbines, because the sodium sulphate is water soluble, and that gives a means of cleaning the turbine blades.

I can give an example which will illustrate that point. A particular gas turbine was run on a gas oil blended with a straight residual fuel; the ash content was 0·03 per cent, of which 15 per cent was vanadium and 16 per cent sodium. Of the deposit 80 per cent was water-soluble, and that water-soluble portion contained all the sodium sulphate formed and a large proportion of the total vanadium present. The same machine was then run on a straight-run fuel oil blended with a cracked residue and Edeleanu extract. The ash content of this fuel was 0·05 per cent, and the ash contained 40 per cent vanadium and 1·8 per cent sodium. Only 40 per cent of the deposit was water-soluble.

Dr Bowen mentioned the difficulty he had of catching the deposits from a heavy fuel combustion chamber. We have had the same problem, and I would suggest that in order to get these deposits from a residual fuel the presence of carbon in the exhaust gas stream must be avoided; a high combustion efficiency is necessary. It has been found an advantage in some cases to use a distillate fuel with added ash constituents consisting of oil-soluble salts of vanadium and sodium.

The next point raised concerned the corrosion effect of various ash deposits. The particular work to which I was referring was done in the laboratory on small specimens of various heat-resisting alloys in the presence of a number of solid or gaseous corroding agents which could conceivably occur in actual gas turbine operation. Sodium chloride was the most corrosive substance examined, while sodium sulphate was one of the least corrosive. Vanadium pentoxide occupied an intermediate position, although it attacked very strongly any material containing molybdenum. Sodium *meta*-vanadate was, in general, more corrosive than vanadium pentoxide and considerably more corrosive than either sodium *pyro*- or

ortho-vanadate. We do not know to what extent sodium *meta*-vanadate deposits can occur or what conditions in the combustion chamber can give rise to this also undesirable product.

T. F. HURLEY: With regard to the fineness of the fuel used in the coal-burning appliances, in the straight-through combustion chambers it has been shown that the finer the fuel the better. But the finer the fuel, the most costly it is to grind, and one has to compromise. In gas turbine work the compromise is to grind so that about 90 per cent of the fuel passes a 200-mesh sieve; that is in contrast to something of the order of 70 per cent through 200 mesh as used in boiler practice. In the vortex combustion chamber we use about 80 per cent through 200 mesh.

With regard to the temperature in the vortex combustion chamber, in the Fuel Research Station design we use something approximating to the stoichiometric air in the combustion chamber, and the diluting air is introduced after combustion is completed. The fuel is carried into the chamber by the primary air through nozzles which are situated two-thirds of the way towards the outside of the chamber. The primary air is given a direction such that it does not upset the streamlines set up by the air coming in at the circumference.

Coming to the problem of slagging in the cyclone chamber, that chamber was not designed by the Fuel Research Station, but was designed by the BCURA for us. Mr Battcock, who is in charge of that work, is here, and I suggest that he be asked to deal with it.

W. V. BATTCOCK: I am not sure that the question should really be directed to me, because it referred to the possible spalling of the refractory in the chamber, and I think the chamber which Dr Bowen had in mind was the Fuel Research Station design.

However, in the BCURA chamber the walls are made of mild steel tubes wound into a helix; cooling water being passed through the tubes. Initially the inner surface of the walls has a thin layer of plastic refractory pasted on. In the course of operation the refractory layer becomes "amalgamated" with slag and reaches an equilibrium thickness on the tubes, this thickness depended primarily on the "effective" flame temperature and the temperature at which the molten slag flows down the surface. In this way the life of the chamber is not dependent upon the resistance of the refractory to slag attack.

With this form of construction there is a danger that the layer of frozen slag on the tubes may flake off, particularly when stopping or starting, and to reduce the danger the tubes are covered with a large number of studs welded on. The water-cooling is only an experimental expedient. In a practical combustion chamber it would not be desired to throw away the heat which is lost to the walls, and which may amount to between 10 and 20 per cent of the heat released in the chamber; it would be desirable to transfer it to the working air, and a chamber in which the cooling is done by the working air is the objective. Preliminary investigations indicate that such a design is practicable.

One of the advantages of using water cooling for the first experimental chamber is that it enables the rate of heat transfer to the walls to be

measured accurately, and this provides data for the design of an air-cooled chamber.

MR HURLEY: With regard to the vortex chamber, the circumferential wall is made of common refractory cast in the form of a series of triangular shapes so that there is a series of nozzles coming through the wall, and each section is swept by the air coming from the nearest nozzle. In practice, although only cheap materials are used and we use only stoichiometric air in the chamber, the only deposition we have had—and I am glad to say we have overcome it now—has been carbon deposition on the walls resulting from bad design and bad construction in the primary air nozzles, which caused the powdered fuel to impinge on the walls and to form a sort of sintered-carbon deposit. We are able now to operate for long periods without any sign of build-up on the walls.

The refractory is used, of course, to give a certain amount of heat to assist ignition and to improve the flexibility of the chamber.

The vortex principle is used in America for gasification, using oxygen and steam; in that case the chamber is slagging, and the temperature, of course, is very much higher. But the conditions are quite different from those obtaining in our vortex combustion chamber.

MR H. A. CHEETHAM: A question has been put by Dr Bowen as to what sort of combustion was obtained. I am not very clear about what he means, and all I can say is that there was a blue flame, very much over-rich, in contrast to the normal combustion chamber, where there is an intense yellow flame. A possible explanation is that the combustion chamber was operating at atmospheric or lower pressures. The diameter was about half that used in present-day combustion chambers. The combustion-chamber efficiency was not measured, but work is in progress at the moment on combustion efficiency; and if Dr Bowen can persuade Professor Garner to invite him to the Department he can see the results we have obtained so far.

B. P. MULLINS: I am interested to see that in so far as the combustion of distillate fuels in gas turbines is concerned there is now universal agreement that the effects of physical variables far outweigh the effect of chemical variables.

My own eight years' practical experience of combustion under aero gas turbine conditions is in harmony with this conclusion. I have found that although changes in the chemical composition of the atmosphere (air vitiation) may affect combustion-chamber performance (combustion efficiency, flame length, chamber stability) to an even greater extent than do changes in fuel composition, in all cases an appropriate adjustment of one or more physical variables can neutralize these effects. Thus air preheating can offset the effects of air vitiation,* and alterations in local air/fuel ratios can negative the greater coking tendency of highly aromatic fuels.†

Mr Scott's laboratory results that sodium chloride rapidly attacks turbine

* Barr, J., and Mullins, B. P. *Fuel*, 1949, **28**, 225. "Combustion in vitiated atmospheres. Part IV—Performance of a typical combustion chamber."

† Staff of Combustion Department. N.G.T.E. Report No. P.J.R. 1008, August (1944). "The coking characteristics of gas turbine fuels."

materials at high temperatures reminds me of Messrs John Brown's practical experience *—they added carbon tetrachloride continuously to the combustion air in an attempt to induce the easy vaporization of the vanadium in the fuel as a chloride, but very extensive corrosion of the heat exchanger resulted, due largely to the chlorine present in the combustion products.

Mr Dawson's observation that in general carbon formation in upstream regions of a combustion system appears to be due to liquid-phase fuel cracking, whereas downstream coking appears to originate from gaseous fuel cracking, agrees with my engine and rig-test observations in 1944.† In these tests the upstream coke deposits had a wavy surface structure as if a viscous liquid had been blown by an air stream whilst the tertiary zone carbon deposit was like soot and, unlike the upstream deposit, could be blown away.

Mr Dawson's statement that the stability of his miniature combustion chamber when using gaseous fuel correlates with the known inflammability limits of homogeneous fuel–air mixtures, suggests that flame-propagation inability plays a major part in determining the weak limit. The further result stated by Mr Dawson that quartz combustion tube stability characteristics using non-homogeneous mixtures do not correlate with inflammability limit data, indicates that other factors are important in this case. In my view such factors are most probably the rate of formation of zones of near-stoichiometric fuel vapour and air in the primary zone (vaporization and mixing) and the spontaneous ignition properties of these " pockets " of inflammable mixture.

Little or no reference to the possible importance of the magnitude of the ignition delay of fuel–air mixtures in influencing combustion-chamber stability has been made in the papers presented at this symposium, an omission which I criticize, although it may be due merely to the realized difficulty of defining the relevant thermal conditions of a fuel–air mixture in a highly turbulent region like a combustion chamber. It seems to me probable that the ignition delay of a fuel–air mixture is important in determining whether or not combustion occurs under a given set of practical conditions when those conditions are near the extinction threshold, *e.g.*, low-pressure (high-altitude) combustion or combustion near the weak stability limit conditions.

I am in strong agreement with Mr Dawson that further work on the aerodynamics of combustion chambers and relevant data on the ignition delay of fuel–air mixtures are urgently needed to assist combustionists in achieving a fuller understanding of gas turbine combustion.

It is interesting to note from Mr Hurley's paper that yet a further case of " combustion with recirculation " has arisen, in this case a coal-burning chamber. I should expect that the effect of the air vitiation *per se* would be greater here than in the case of hydrocarbon combustion, since a solid fuel does not diffuse outwards to meet the oxygen-impoverished atmosphere, and a large reduction of reaction rate may therefore occur. Of course, higher local air temperatures may more than offset this handicap.

Mr Hurley stated that in the cyclone coal-burning combustion chamber

* Bucher, J. B. *Oil Engine and Gas Turbine*, May 1950, **18** (205), 13.

† Staff of Combustion Department. N.G.T.E. Report No. P.J.R. 1003, August (1944). "The coking characteristics of gas turbine fuels."

the fuel particles rotate in spiral or circular paths under the action of two balanced forces, the inward force arising from the inward component of air velocity and the outward centrifugal force. I cannot understand this, since a moving particle acted upon by two equal and opposite forces can move only in a straight line. I think that the fallacy arises from the confusion of a central orbit problem with the problem of a particle rotating on a string, and may be resolved by deleting any reference to "centrifugal force," which is non-existent in the present case.

I should like to ask Dr Cheetham whether he has investigated the effect of linear scale upon the stability loops of his combustion system. Also, would he let me know, please, what type of fuel meter was used to handle such a small liquid flow as 50 cc/hr?

MR HURLEY: I must agree with Mr Mullins that a moving particle acted upon by two equal and opposite forces can only move in a straight line and that, strictly speaking, it is incorrect to say that in the vortex chamber centrifugal force is balanced by the inward drag of the air. The justification for using the statement is that it enables the average engineer to grasp very quickly the practical application of the principles of combustion used in the vortex chamber.

J. G. DAWSON: There is very little on which I need comment, for I am pretty well in agreement with Mr Mullins.

On the question of carbon, however, I think I should modify the statement that in the upstream case it is all wet cracking and in the downstream it is all quenching from the flame, and say that in the upstream the wet cracking preponderates. I think we can get the other type as well.

I would also agree with Mr Mullins that, although I have been trying to plead that we should make combustion chambers as insensitive to the chemical composition of the fuel as possible, work is still required on that aspect, and that, as I said in my paper, ignition delays could with advantage be studied further.

MR CHEETHAM: Mr Mullins has raised the question of scale effect. We did not investigate that because of the shortage of time and money.

With regard to the ignition theory, I think the influence of the spontaneous ignition temperature of the fuel in gas turbine combustion chambers has been (and this is merely a personal opinion) rather over-emphasized. I think that, once a stable flame has been established in *this* region by the action of the vortex, you have so many free radicals and such a high temperature knocking around that zone that they will ignite the fresh vapour from the droplets under quite different conditions from those applying in the spontaneous ignition of that vapour where there was not a flame already established. (*Sketch.*)

I agree with Mr Mullins that at the lower pressures the colour of the flame is green. At pressures up to one-seventh of an atmosphere I find the flames are very green, and with increasing pressure they graduate to blue. It is a rather interesting point, but I just do not know the explanation.

The rotometer, which would measure up to 2 cc/min, was vertical having a normal float, and we found that the viscosity dependence of the roto-

meter was one over very large areas; we had to thermostat the rotometer and put in a spiral coil for the incoming fuel.

J. J. MACFARLANE: In the matter of the relative depositions of sodium and vanadium, we have been making experiments which are somewhat similar in principle to those described by Mr Scott. It has been found that, for equal weight concentrations of sodium oxide and V_2O_5 in the kerosine, at 600° C with a given combustion system the ratio of the weight of sodium oxide in one experiment to V_2O_5 in the other was 2 : 1, whereas at 700° C they were approximately equal. It is interesting that, on mixing the sodium and vanadium together in the same solution, there seems to be very much less sodium deposit. Further, the small amount of sodium associated with the vanadium in the deposit seems to alter the properties of the ash quite markedly, in that there is a very large increase in deposition rate at intermediate temperature.

The corrosion produced by vanadium pentoxide is very much a function of temperature, and the melting point of V_2O_5 is a very important factor in the process. If the rate of corrosion is plotted against temperature there is a sharp upward inflection of the curve at a temperature more or less in agreement with the melting point of V_2O_5—which incidentally is said to be 690° C, but which we find by two different methods to be 673°.

With regard to Mr Scott's pious hope that the use of carbon blanketing by controlling combustion may eliminate the corrosion problem, I can only say that we have been working at the NGTE, as Mr Hurley has said, with a vortex type of chamber for burning heavy fuels; in those chambers we have some control of the amount of carbon in association with the ash in the gases, and even when working under the most favourable conditions for producing such an association of carbon we find that the small amounts of vanadium which are deposited will produce quite a serious corrosion problem. From our present experience, at any rate, it does not seem that we can hope to eliminate the problem completely by that means; it seems that we can control the rate of that deposition to prevent the building up of physically large deposits which would interfere with the aerodynamic behaviour of the turbine blades, but I do not think we can overcome the corrosion problem.

Work on the corrosion inhibition problem is still *sub judice*.

MR SCOTT: In some ways the figures Mr Macfarlane has given for the deposited weights of sodium and vanadium seem to bear out our experience, but the matter depends very largely, I think, on the combustion system used, and for this work the methods employed by NGTE and ourselves may have been very different.

Another point to be borne in mind is that, when using these synthetic ashes, the fuel has to be prepared very carefully, and we found it necessary to use heated kerosine, the reason for that being that the sodium naphthanate used for simulating the sodium ash comes out of suspension or solution when the fuel is cool; I think Mr Macfarlane used cool or cold kerosine in his work, and therefore he may have lost or may not have had the concentration of sodium present in the fuel that he thought he had.

It is very nice to know that the melting point of vanadium pentoxide is

confirmed at 673° C. I have seen vastly different melting points quoted, and I think the reason is that it is extremely difficult to get a pure sample of vanadium pentoxide on which to determine the melting point.

With regard to the carbon in the gas stream and its effect on corrosive deposits, it seems to me that the first thing to do is to remove the deposit; it may be necessary to run the turbine at a somewhat lower temperature, slightly below the melting point of the ash. If the deposit is prevented from forming it may be possible to continue running at a somewhat lower temperature, and by that means possibly avoid corrosion. But a lot of work still remains to be done, particularly on the combustion of residual fuels, to avoid both corrosion and ash deposits.

J. J. Macfarlane: When preparing solutions of sodium naphthanate in kerosine, in order to avoid loss such as he has mentioned the solutions are kept continuously agitated.

If Mr Scott discusses operating temperatures with engine designers he will find they will not be too happy to design their turbines to run at temperatures below the melting point of vanadium.

B. H. Mullins: Dr Cheetham asserts that in his opinion spontaneous ignition plays a negligible part in a combustion chamber where there exists a large volume of gases at flame temperature; he thinks that some research workers over-emphasize the importance of spontaneous ignition in combustion systems. I agree with all this in so far as normal combustion conditions are concerned, but should like to remind Dr Cheetham that at the weak stability limit the primary zone is not filled with very hot flame gases.

Professor A. D. Baxter: These papers are most valuable to the engineers and to the chemists alike.

A short time ago I attended a symposium on gas turbine materials organized by the Iron and Steel Institute when vanadium and sodium deposition was discussed; the metallurgists seemed to say that they could not make better materials, so that they must ask the chemists to do something. Now the chemists seem to say that they cannot do anything either, and they must ask the engineers to do something. But I would appeal to the chemists to look into these problems seriously. Mr Dawson has discussed the engineering aspects, and has emphasized that a lot can be done on that side. My answer is that a lot has been done on that side, and that it is now time for the chemists to do something. It was interesting to hear it suggested that, all things considered, kerosine was the best fuel. Perhaps the engineers were extremely fortunate in picking on that in the first place. Mr Dawson has referred to points such as turbulence, ignition energy, and so forth. The engineers use a lot of brute force to get combustion started, and I feel that the chemists ought to be able to help us by finding means of achieving ignition which involve the application of a good deal less energy. The chemists should not hand all the problems back to the engineers.

Mr Scott: There is one aspect I would mention of this problem of handing the job back to the chemist. Really the easiest and cheapest way

to remove vanadium is by distillation; we are then back in the more expensive distillate fuel range. The whole object of using residual fuels is cheapness, and I suggest that the engineer and chemist will have to get together to produce a combustion chamber which will make use of the fuel oil as it is without additional refinery treatment.

J. J. MACFARLANE: The problem of introducing carbon is not so bad as it sounds. Experimental results show that ash deposition can be controlled by the presence of carbon in the ratio to ash of something of the order of 8. A typical residual oil contains up to 0·1 per cent of ash. That means carbon producing something of the order of ½ per cent combustion loss. It is not very much.

In defending chemists in regard to this matter of ignition, and so forth, I would like to say that the trouble, particularly in the case of aero gas turbines, is largely the fault of the design engineer. When he designs a gas turbine, particularly an aero gas turbine, it seems to me that he sets out first and foremost as an aerodynamicist. He will have his turbine here and the compressor there; and then he has an after-thought and says: "We have to have a combustion chamber; where can we put it?" Thus we get the perennial problem of obtaining a very large heat release in a restricted space.

PROFESSOR BAXTER: I had to face precisely that problem myself many years ago.

H. C. RAMPTON: Mr Dawson said that the carbon deposition increased as the gravity increased, and also mentioned gravity against boiling point. I wonder if he meant the mid-boiling point of the fuel or the length or position of the cut of the material. I can postulate two fuels having the same gravity and the same boiling point, one being 50 per cent aromatic and the other entirely devoid of aromatics. Would he then get a correlation with carbon deposition? I am inclined to think he would not.

A point which I do not think I have seen mentioned in any gas turbine paper is the influence of the back end volatility of the fuel. In the paper by Mr Scott and his colleagues there are some figures relating to ASTM distillation tests (Table VI). For the aromatic material the 90 per cent recovery point is 231·5° C, and the FBP is 253·0° C. That is an ASTM test, and we know that the emergent stem correction for the FBP is probably of the order of 10° to 12°; *i.e.*, the real FBP is 265° C. If that material is super-fractionated in (say) a 100-plate column there will probably be 1½ to 2 per cent boiling at above 300° C due to slight entrainment in the ordinary refinery column. Has any work been done on a kerosine type of fuel which has been super-fractionated at the back end to avoid any high-molecular-weight material? Slight percentages of this could form the hard core of the drops, and possibly stick and start the carbon deposition.

I agree with Mr Dawson—and Mr Scott has made the same remark—that the gas turbine problem will not be solved by either the chemist or the engineer separately; they have both to work together and try to marry their knowledge and experience.

J. G. DAWSON: I thought I explained that we used the specific gravity to obtain the correlation, merely as a handy form of expression rather than because it had any significance in itself. The main factors we have found in controlling this type of carbon deposition are the carbon/hydrogen ratio—and I say that deliberately and not aromatic content—and the boiling level. The nearest figure we have found which correlated or which came into the combined correlation of carbon/hydrogen ratio and boiling level was the 90 per cent recovery point figure. That is to say, it is the heavy ends which are important in this case. But here again it is not easy to generalize. I could quote some results where we did fractionate a fuel, and found that a middle cut gave heavier deposition than would have been expected. Generally speaking, however, it is the heavy ends which give the trouble.

B. H. MULLINS: Further to what Mr Dawson and Mr Rampton have just said concerning coke formation, the NGTE found many years ago as the result of engine and rig tests that the weight of deposit varied as the carbon/hydrogen ratio of the fuel, and further that the addition of 1% by volume of light lubricating oil to kerosine almost doubled the rate of carbon deposition.

D. B. SPALDING: I would like to congratulate Mr Topps on his experimental work. He has, however, left us with the difficulty of making use of his results, and I think that difficulty arises chiefly from the form of presentation. His results for the rate of vaporization of droplets falling with their limiting velocities are expressed in terms of grams per erg friction. I plead for the use of the language of the dimensionless group, which can be understood and which does enable one to go from one system to another. The great advances in heat transfer are due to use of this language; it should not be neglected in heat-transfer work. Just what the dimensionless groups are to be in this case it is difficult to say. I do not think any of the usual groups will do, because time does not come into Mr Topps' experiments. I take it that he has not been able to measure the velocity of the droplets, or something of that sort. But if a dimensionless group could be found it would enable Mr Topps' results to be applied in vortex chambers, etc., where it is the distance of travel and not the time of combustion which is fixed by design; and when he has put the results in the form I have suggested it may be found that no one need ever do any experiments on evaporation with droplets falling at their limiting velocities again.

I would like to seize rather unfairly on one word in Mr Dawson's paper. In the second paragraph he states that: "The increased intensity of combustion involves a greater pressure drop or draught loss than is experienced in, say, boilers, through the necessity for producing sufficient turbulence of the air/fuel mixture to complete the burning in the required space." It is the word "burning" with which I quarrel. There is no difficulty about burning at the required combustion intensity; it is the mixing which is difficult. So that there is no fundamental reason for the very large pressure losses which occur in gas turbines, particularly in the aero gas turbine.

The principle on which atomizing combustion systems are based is that it is a good thing to have a high ratio of surface area of fuel to weight of fuel. That is not quite true; a high ratio of surface area to volume of combustion chamber is wanted. That is not what is obtained when we atomize. Certainly droplets are provided to give a high ratio of surface area of fuel to weight of fuel; but because the droplets are released in the air stream they shoot out of the combustion chamber, and there is difficulty in burning them before they get out. Hence the need for turbulence and, therefore, high pressure losses in burning them in the combustion space. The logical method of burning a lot of fuel in a small space is certainly to provide a large area of fuel surface but at the same time to keep the fuel fixed in the space.

I was particularly interested in Mr Hurley's account of the coal-combustion system in which the fuel is deliberately kept on the walls so that the air can blow past quickly. Thus there is a high relative velocity and high combustion rate, but the coal is not shot out almost as soon as it enters the chamber. The same applies in the vortex chamber, I take it, where the fuel remains inside the chamber until it is ready to go out.

The logical application of that idea to the liquid-fuel gas turbine is to provide some fixed surfaces over which the fuel is spread and to let the fuel burn in an air stream, so that there is obtained a short flame an inch or so long, a very high combustion intensity, and low pressure drop. This can be shown experimentally. Moreover, it happens that this type of flame is blue, and therefore deposits no carbon, even with highly aromatic fuels.

Possibly this connects up with the controversy between the chemists and the engineers. The engineers say that they cannot do much to improve the present system, and they want the chemists to help. It may be that when the engineers take up the combustion system I have advocated, their demands on the chemists will be reduced because of insensitivity of the system to fuel properties.

J. E. C. Topps: I thank Mr Spalding for his kind remarks. I rather think that he has exaggerated a little, however. I assure him that there is nothing I should like to be able to do more than to express results in a manner in which they can be more readily applied, and so that they will give rather more than an indication of what is relevant in the evaporation process. But we are up against the difficulty of getting the right kind of measurements under the experimental conditions. The only alternative which so far appears practicable when using small droplets is measurement of burning life and relative velocity, which would not alone, give much more information, and which would be difficult to combine with collection of residues.

Mr J. G. Dawson: I think Mr Spalding rather contradicted himself. He said one of the troubles is that the droplet is shot out of the chamber before it is burned. That was the point I was really driving at. I suggest that probably it is the word "turbulence" that he would really wish to change, and perhaps it would meet his case if I said: "producing sufficient organized swirl and turbulence to complete the burning."

J. J. MACFARLANE: I am going to defend the engineers. Mr Spalding may not know that as long ago as 1941, and even a year or two before that, Sir Frank Whittle was doing his best to make the fuel sit still and the air whistle past it, by using such things as wicks for aero gas turbine combustion chambers. But if Mr Spalding wants to overcome this difficulty I would suggest to him that some quite useful work in the use of the vaporization has been done and applied practically with a great measure of success.

T. F. HURLEY: May I suggest that the words we are looking for are really "relative motion," and that the engineer found its value when he constructed the first hand-fired grate. With this you can burn the carbon as quickly as you like merely by blowing air more quickly through the fuel bed.

B. H. MULLINS: I find Mr Spalding's suggestion of holding the fuel stationary in a combustion chamber and allowing the air stream to pass by it an interesting one and sound in principle. However, this method needs to be demonstrated on the scale of and at the operating pressures of the full-size combustion chamber before any extravagant claims concerning greatly increased combustion intensities have any practical weight; when this is done I shall be a fervent protagonist of this new method of fuel admission.

G. A. E. GODSAVE: Mr Topps has made reference in his paper to some unpublished theoretical work of mine on the conduction of heat to the interior of droplets. I would like to say a few further words about this work, which concerns the mechanism of cenosphere formation in heavy fuel drops.

Brief reference was made to these investigations in the recent lecture to the Institution of Mechanical Engineers by Mr Lloyd and Mr Probert * on "The problem of burning residual oil in gas turbines," and some of the relevant curves were shown. In short the story is as follows. As Mr Topps has so elegantly demonstrated with his experimental technique, there is a threshold ambient temperature above which cenosphere formation does not occur with heavy fuel drops. These laboratory observations are also borne out in practice by operating experience on the balanced-vortex type of heavy fuel combustion chamber at the National Gas Turbine Establishment. The threshold temperature is about 700° C, and above it small coke-like residues (the more desirable end-products) are obtained, whereas at lower ambient temperatures cenospheres are formed, with all their attendant disadvantages in practical combustion systems.

The calculations referred to suggest that these results may be explained by reference to the rate at which the interior of the drop increases in temperature. Further confirmatory work is projected, but the present indications are as follows. There is a race, as it were, between the rate at which the drop decreases in size and the rate at which the interior gets hot. At the higher ambient temperatures the evaporation rate is sufficiently great that the interior of the drop does not get really hot until near the end of the drop life. The ultimate residue is then a hard, coke-like residue formed from the last

* Lloyd, P., and Probert, R. P. *Proc. Inst. Mech. Engrs.*, 1950, **163**, 206.

remaining fractions of the drop. At the lower ambient temperatures the evaporation rate is comparatively slower. Consequently, the interior of the drop can reach the maximum temperature corresponding to the drop surface temperature perhaps half-way through the drop life. For the remainder of the drop life (which is in this case anyway extended) the interior of the drop can thus soak at this elevated temperature. This would clearly tend to lead to the evolution of gases within the body of the drop (due either to volatile materials already present or to cracking), with consequent swelling and the formation of cenospheres.

I would like now to say a few words in connexion with Mr Dawson's paper. I was particularly interested in the curves that he presented in Fig. 1, in which significant differences between different fuel types were apparent under certain conditions. It is perhaps fortunate from the point of view of both fuel producers and fuel users that, at least in the distillate fuel range, fuel characteristics appear to play a minor role in the gas turbine combustion process under normal operating conditions. There is, for example, at present no major effect of the chemical constitution of the fuel corresponding to the problem of knock in the reciprocating engine. However, when differences between fuels do manifest themselves under gas turbine conditions it is naturally desirable to attempt to explain these differences.

At the National Gas Turbine Establishment we have concerned ourselves in some detail with the fundamentals of spray combustion and the influence of fuel characteristics. To this end we have studied in particular the history of the single drop. The technique employed for heavy fuels and a selection of the results obtained have been described by Mr Topps. In the case of distillate fuels a method that has provided useful information has been to photograph with a cinematograph camera single burning drops suspended in still air on a fine silica filament.

Among the results obtained using the silica-filament technique there may be mentioned the fact that it has been shown that the burning drops decrease in size at a mass rate proportional to the first power of their diameters. This leads to the result that the total drop life is proportional to the square of the initial diameter.

The results of this investigation show further that the volatility of the fuel, as expressed by the normal vapour pressure, does not have a predominant effect in determining the burning rate. Instead, the rate of decrease in size is determined by the rate of heat transfer to the drop, and so the important fuel characteristic is the heat necessary to evaporate unit mass of the fuel. Fuels differing in this latter respect would thus be expected to exhibit different performances when burnt in a spray, other things being equal.

In the case of liquid fuel drops, as distinct from solid fuel particles, there is no chemical consumption of the material of the drop at the drop surface. The flame front is formed at a distance removed from the drop, and the material of the drop is evaporated off and so feeds the flame front.

Since it is thus apparent that the only way the liquid drops in a distillate fuel spray can decrease in size during combustion is by evaporation, we have

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* Godsave, G. A. E. *Nature*, 1949, **164**, 708.

naturally studied this process in some detail at the National Gas Turbine Establishment. The so-called burning rate of the drop is really its evaporation rate under the particular conditions of heat transfer concerned.

In certain cases it has been possible to solve the appropriate equations of gas-phase conduction under the complex conditions of heat and mass transfer in the neighbourhood of the drop. The effect of the mass transfer from the drop is to reduce the heat-transfer coefficient to a value approximately one-half that of a non-evaporating sphere under similar conditions. By equating the calculated values of the heat transfer, with due allowance for any significant radiation effects, to the amount of heat necessary to evaporate the fuel, theoretical values of the burning rates can be calculated. The latter are in good agreement with the measured values. This indicates that the suggested mechanism of decrease in size of burning drops is correct.

These investigations show clearly the respective distinctions between the mechanisms of decrease in drop size under low-temperature conditions (as when raindrops evaporate at atmospheric temperature) and high-temperature conditions (as when liquid fuel drops evaporate during the combustion of a fuel spray). In the first case the rate of decrease in drop size is determined by diffusion processes, and in the second case by heat-transfer processes.

It follows that as far as each individual drop is concerned the factor that influences its life in a combustion chamber is the temperature field in the chamber. Any modifications of the temperature field due to the aerodynamic flow pattern, chilling, etc., would tend to modify the drop life. The importance of mixing in establishing a favourable temperature field is evident. This fits in with the general picture of the importance of the aerodynamics of the combustion process that Mr Dawson so rightly emphasized in his paper.

It is reasonable to suggest that any observed differences in performance between fuels with similar physical properties, but of differing chemical types, may in fact be due to variations in chemically dependant factors such as ignition and gas-phase combustion characteristics (particularly under adverse conditions such as low pressure) giving rise to different temperature fields, and so causing differences in drop lives.

To summarize, we may say that the rate of decrease in size of each drop in the burning fuel spray is controlled by the temperature field. In turn, the temperature field depends upon the chemical combustion characteristics in the gas phase and upon the aerodynamic mixing.

The investigations so far discussed refer to the individual drops in the spray. The next stage is to discuss the combustion of a cloud of drops in a spray. In this connexion it is necessary also to determine how the drop lives determined under laboratory conditions compare with drop lives under chamber conditions in the presence of forced convection, enhanced radiation, etc. As a first step in this direction the following results are of significance. Some time ago Mr Probert * published a theoretical analysis of the lifetimes of burning kerosine sprays, allowing for particle-size distribution by means of the Rosin–Rammler distribution law, and expressing the drop life in terms of a constant λ, called the evaporation constant. At the time this

* Probert, R. P. *Phil. Mag.*, 1946, **37**, 94.

work was published experimental values of λ for burning drops were not available. However, using the silica-filament technique described, it has now been possible to determine the values of the evaporation constant λ for a series of pure hydrocarbons and commercial fuels. Using Mr Probert's analysis, calculations have been made to see how the calculated spray-life times, based on the rates of burning as determined in the single-drop experiments, compare with the times available in actual aircraft chambers, based on the chamber volume, air mass flow, pressure, and temperature. The calculated spray-life times are found to be of comparable order to the available times, the latter being, for example, of the order of 6 to 8 milliseconds. For complete combustion in the available time it appears that the value of the evaporation constant λ obtaining in the spray is about $1\frac{1}{2}$ to 2 times the value measured in the laboratory experiments. The inference is that the change in λ, due to the effect of neighbouring drops in the spray, turbulence, increase in radiation effect, and other chamber conditions, although appreciable, is not as pronounced as might have been thought earlier. This being so, it would appear that the conclusions drawn from the laboratory experiments with regard to the quantitative effect of the variables concerned have a direct bearing on gas turbine combustion as it occurs in practice.

J. G. Dawson: Mr Godsave's work provides an explanation for the effects shown in Fig. 1 of my paper, but similar differences are shown in Fig. 4 which presents data obtained on a system using vaporized fuel. The main difference shown in this figure was between two isomers, triptane and *n*-heptane, and the only suggestion I can make at the moment is that the heptane gave the wider stability limit because it is the more easily oxidizable of the two. Thus, some factor involving the rate of oxidation, as well as those indicated by Mr Godsave, can influence combustion under certain conditions.

B. H. Mullins: Mr Dawson wonders what fuel properties under gas turbine conditions are analogous to those determining good combustion in reciprocating engines and diesel engines. From my own experiments I have evidence that the ignition delay of fuel–air mixtures at high temperatures (greater than 900° C) may sometimes correlate directly with such properties as octane number and cetane number; I am actively working upon this subject at the moment, and am not yet in a position to give fully confirmed conclusions, although I can say that ignition temperatures at long delay times (*e.g.*, laboratory bomb data) seem to be irrelevant where engine applications are concerned.

Vote of Thanks

The Chairman: We have had an extraordinary good discussion, and it remains for me to express our thanks to the authors for their excellent papers and for the way in which they have replied to the points raised in the discussion. I will invite you now to join me in expressing appreciation.

(The vote of thanks was carried with acclamation, and the meeting closed.)

n-HEPTANE AS A STANDARD SOLVENT FOR THE ASPHALTENE DETERMINATION IN ASPHALTIC BITUMEN *

By E. Eisma and C. J. Krom †

Summary

For the determination of the asphaltene content in asphaltic bitumens different countries prescribe different solvents, mostly aromatic-free gasoline fractions. Consequently for one bitumen different values of the asphaltene content are found, and this gives rise to confusion. In addition, different asphaltene contents may be found as a result of differences in chemical composition between gasoline fractions lying within the specification limits.

These drawbacks may be met by the universal use of one pure solvent, for which normal heptane is suggested.

One of the means of characterizing asphaltic bitumen is to determine its content of insolubles in various solvents. In some of these, such as carbon disulphide, benzene, carbon tetrachloride, and *cyclo*hexane, normal asphaltic bitumens generally dissolve almost completely. Others, such as light aromatic-free gasolines, pentane, and ether, only partly dissolve asphaltic bitumen as a rule. The insoluble part is mostly called asphaltenes, a term coined by Marcusson.

Historic development has led to the prescription of different solvents in different countries for the determination of asphaltene content. The Institute of Petroleum (U.K.) specifies for this purpose IP Petroleum Spirit, the American Association of State-Highway Officials (A.A.S.H.O.) 86° Baumé naphtha, while in Germany "Normal-benzin" and in the K.V.B.B. (Test specifications for bituminous building materials of the Dutch standardization committee) chemically pure ether is used. In addition to these officially prescribed solvents use is made of other types, such as *iso*pentane.[1] The specifications of the standardized solvents are sumarized in Table I.

The use of different solvents will cause variations in the figures found for asphaltene content of a certain bitumen.[2] For this reason the term asphaltenes is in itself not sufficient but requires some additional characterization according to the solvent used, *e.g.*, 60/80 asphaltenes, pentane asphaltenes, etc.

From an analytical point of view it would no doubt be an advantage if one standard solvent were generally accepted, because the values obtained with the various solvents in use are not directly comparable. However, none of the standardized solvents has such advantages over the others as to warrant its suitability as universal solvent.

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* In the autumn of 1947 the authors started an investigation into the relationship between internal pressure of pure solvents and the solubility of bitumens in these solvents. The results were partly communicated by Prof. H. Eilers at the 1948 Spring Meeting of the American Chemical Society (see also J. Ph. Pfeiffer: "The properties of asphaltic bitumen," Elsevier, 1950, pp. 28–31).

As well as the theoretical aspect this investigation had a practical one, viz., the determination of asphaltenes. The latter aspect is dealt with in this paper.

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TABLE I

Specification of Solvents Used for the Asphaltene Determination

	IP petroleum spirit	86° Baumé naphtha	"Normal-benzin"
(*a*) Specific gravity (IP 59)	0·680–0·690 (60/60° F)	88–86° Bé. = 0·642–0·648 (15/15° C)	0·695–0·705 (15/15° C)
(*b*) "Doctor" test (IP 30)	Negative	—	—
(*c*) Colour (IP 17)	Waterwhite (1·0)	—	—
(*d*) Distillation test (IP 123):		Not specified	
I.B.P.	55° C (min)		65° C*
Between 60° and 80° C	90% by vol. (min)		—
F.B.P.	90° C (max)		95° C
(*e*) Aromatic content (IP 3)	<0·5% wt		<2% vol.
(*f*) Bromine number (IP 9)	<1		—
(*g*) Aniline point (IP 2)	58–62° C		55–62° C
(*h*) Residue on evaporation (IP 38)	<10 mg/100 ml		—

* Slightly modified distillation method.

Standardized gasoline fractions have the drawback that within their specification limits considerable differences in composition may occur, which means that the asphaltene values found with them will vary accordingly.

To demonstrate this effect asphaltene determinations were made on four different bitumens with two IP spirits differing in composition. The properties of the spirits and results obtained with them are given in Table II. Statistical analyses have shown the differences in asphaltene contents found to be significant with more than 99 per cent certainty for each bitumen sample.

TABLE II

Properties of and Results with two IP Spirits

	Specification	IP spirit No. 1	IP spirit No. 2
Spec. gravity (60/60° F)	0·680–0·690	0·690	0·683
Distillation:			
I.P.B., °C	55 (min)	56	57·5
Between 60–80° C	90% (min)	>90%	>90%
F.B.P., °C	90 (max)	77	87
Aniline point, °C	58–62	58·1	61·8
Hydrocarbon group analysis: *			
C_N, % wt	—	*ca* 30	*ca* 23
C_P, % wt	—	*ca* 70	*ca* 77
Asphaltene contents, % wt (IP 7) obtained with: Middle East 40/50 propane bitumen	—	5·45	7·29
Middle East 40/50 distilled bitumen	—	11·99	13·34
Mexican 40/50 distilled bitumen	—	18·59	20·65
Venezuelan blown bitumen 85° C softening point	—	26·72	27·82

* In the hydrocarbon group analysis the percentages of carbon present in aromatic (C_A), naphthenic (C_N), and paraffinic structure (C_P) are determined.

Thus a mean difference in asphaltene content of *ca* 1·6 per cent by wt is found when using these two IP spirits.

This drawback is eliminated by using pure substances. Ether, however, like pentane, gives rise to difficulties in the tropics owing to its great volatility. Pure hydrocarbons with higher boiling points were scarce when the original specifications were drawn up. At present *n*-heptane and *iso*-octane (2 : 2 : 4-trimethyl pentane) of sufficient purity are commercially available at reasonable prices, so that it was investigated whether one of these might be a suitable universal solvent. To this end the asphaltene contents of a series of asphaltic bitumens in *n*-heptane and *iso*-octane were compared with those in pentane, ether, IP petroleum spirit, and 86° Baumé naphtha. All the determinations were carried out at room temperature to eliminate temperature influences. The results are summarized in Table III.

TABLE III

Asphaltene Content % wt of some Bitumens with Various Solvents

Bitumen	*n*-heptane	*iso*-octane	*n*-pentane	Ether	IP petroleum spirit	86° Baumé naphtha
Mexican 40/50	25·7	32·2	33·5	23·0	23·8	28·2
Venezuelan 40/50	17·2	21·4	21·4	14·6	16·4	21·3
Venezuelan 180/200	14·3	18·1	17·3	12·0	13·0	—
Egyptian 170/210	17·5	21·2	21·9	15·2	17·5	—
Middle East I 80/100	9·8	14·9	15·8	7·9	8·9	15·3
Middle East II 170/210	10·1	14·6	15·1	8·3	9·1	—
Trinidad 170/210	7·4	10·4	11·4	4·8	7·1	—
Argentine 230	13·1	20·1	19·5	16·2	11·6	—
Netherlands	—	6·2	7·0	4·7	0·2	—
Highly cracked bitumen	29·4	—	—	16·4	26·4	—
Java S.B. 40/50	11·8	—	—	6·9	11·5	—

These data show that the asphaltene contents of the various bitumens in *n*-heptane are on the whole only slightly higher than in IP petroleum spirit. Also the differences between *n*-pentane, *iso*-octane, and 86° Baumé naphtha are small; those between the two groups of solvents are far greater. The asphaltene contents determined in ether are in general somewhat lower than those found with IP spirit. However, it should be borne in mind that both the nature of the bitumen and that of the solvent may influence the asphaltene contents.

The advantage of both *n*-heptane and *iso*-octane is that they are pure substances, so that the drawing-up of rigid specifications presents no difficulties. Another advantage is that, unlike gasoline fractions, pure hydrocarbons can be recovered for further use. The boiling points of these solvents are 98° and 99° C respectively, and they are thus also suitable for use in the tropics.

Another point is, whether the determination of the asphaltene content can be carried out more accurately with IP spirit or with a pure hydrocarbon, *e.g.*, *n*-heptane. Therefore the repeatability, which is a measure of the non-systematic errors, was determined both for IP spirit and for *n*-heptane as solvent in the asphaltene determination.

Statistical treatment of duplicate asphaltene determinations in 180 samples of bitumens (see Fig. 1), made according to IP 7/42 and with

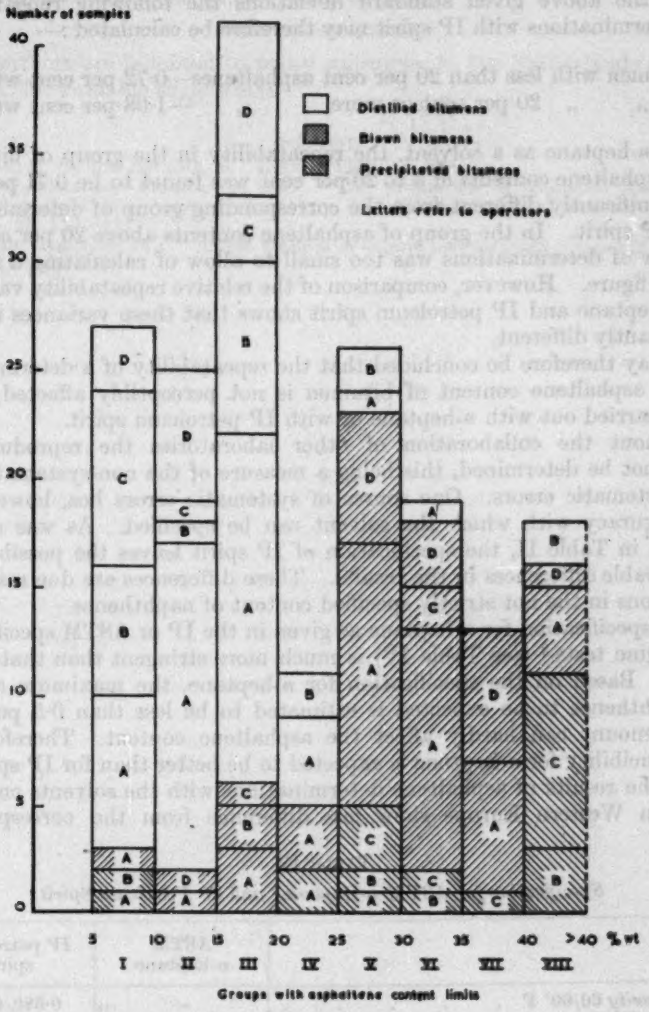
Number of samples
Distilled bitumens
Blown bitumens
Precipitated bitumens
Letters refer to operators
5 10 15 20 25 30 35 40 >40 % wt
I II III IV V VI VII VIII
Groups with asphaltene content limits

FIG. 1

FREQUENCY CHART

IP spirit as a solvent, gave the unexpected result * that the repeatability standard deviation for all bitumens with asphaltene contents between 5 and 20 per cent proves to be 0·26 per cent, for all bitumens with asphaltene

* In IP 7/42 the "repeatability" of the asphaltene determination is given as 5 per cent of the average asphaltene content. This includes the assumption that the repeatability is proportional to the asphaltene content. Statistical analysis of the data shows that this assumption should most probably be rejected.

contents above 20 per cent it proves to be 0·38 per cent. It was shown that the method of manufacturing the bitumen did not affect these figures. From the above given standard deviations the following repeatability for determinations with IP spirit may therefore be calculated :—

Bitumen with less than 20 per cent asphaltenes—0·72 per cent wt.
„ „ 20 per cent or more „ —1·08 per cent wt.

Using *n*-heptane as a solvent, the repeatability in the group of bitumens with asphaltene contents of 5 to 20 per cent was found to be 0·71 per cent, not significantly different from the corresponding group of determinations with IP spirit. In the group of asphaltene contents above 20 per cent the number of determinations was too small to allow of calculating a repeatability figure. However, comparison of the relative repeatability variances for *n*-heptane and IP petroleum spirit shows that these variances are not significantly different.

It may therefore be concluded that the repeatability of a determination of the asphaltene content of bitumen is not perceptibly affected by its being carried out with *n*-heptane or with IP petroleum spirit.

Without the collaboration of other laboratories the reproducibility could not be determined, this being a measure of the non-systematic plus the systematic errors. One source of systematic errors lies, however, in the accuracy with which the solvent can be specified. As was demonstrated in Table II, the specification of IP spirit leaves the possibility of appreciable differences in the results. These differences are due mainly to variations in the not strictly specified content of naphthenes.

The specification for *n*-heptane as given in the IP or ASTM specification for engine tests [3] (see Table IV) is much more stringent than that for IP spirit. Based on the specification for *n*-heptane, the maximum amount of naphthenes to be expected is estimated to be less than 0·5 per cent. This amount can hardly affect the asphaltene content. Therefore the reproducibility for *n*-heptane is expected to be better than for IP spirit.

As the results of asphaltene determinations with the solvents currently used in Western Europe show less difference from the corresponding

TABLE IV

Specification for ASTM n-*Heptane* and IP Petroleum Spirit*

	ASTM *n*-heptane	IP petroleum spirit
Spc. gravity 60/60° F	—	0·680–0·690
Density 20° C, g/ml	0·6837–0·6839	
n_D^{20}	1·38770–1·38785	—
Freezing point, ° C (min)	−90·48	—
Distillation :		
I.B.P., ° C (min)	—	55
Between 60–80° C, % vol (min)	—	90
F.B.P., ° C (max)	—	90
Dist. temp., ° C 50% dist.	98·39–98·49	—
ΔT ° C, 20–80% dist. (max)	0·2	—
Aniline point, ° C	—	58–62

* This specification is nearly equal to that given by the IP.

figures found with *n*-heptane than those obtained with *iso*-octane, *n*-heptane (according to the specification in Table IV) is suggested as the most suitable pure hydrocarbon for universal standardization.

ACKNOWLEDGMENT

The authors are indebted to many colleagues in the Netherlands and in the U.K. for valuable suggestions.

References

[1] Hillman, E. S., and Barnett, B. *Refiner*, 1939, **18**, 533.
[2] See, for instance, Pfeiffer, J. Ph. "The properties of asphaltic bitumen." Elsevier Publ. Co., Amsterdam 1950, p. 28; Eilers, H. *J. phys. & coll. Chem.*, 1949, **53**, 1195–1211.
[3] IP 44/49, Appendix IV; "ASTM manual of engine test methods for rating fuels—1948," page 111.

SOME CRITERIA FOR COMMERCIAL SPECTROMETERS. PART II—COMMENTS BY MANUFACTURERS *

By J. G. Reynolds †

The motive behind the preparation of this paper was mainly to provide the prospective purchaser of a spectrometer with a " yardstick " against which to measure the instrument of his choice and also to keep the manufacturers in touch with the requirements of industrial and academic operators. The possibility that some of the desirable features might be mechanically or economically impossible to achieve was not allowed to affect the criteria employed, and the fact that American instruments, to a great degree, are not available on the European market was not considered. Part I of the paper was submitted to four American and three British manufacturers, who responded with the following helpful criticism and advice.

Cost

In the first place, most manufacturers agree that the instrument cost depends mainly on the amount of research which goes into its production and the number sold, rather than the cost of individual components, although in general, the cost increases with resolution desired, and hence with prism size. Plant instruments can only be made much cheaper than research instruments if the former are mass produced. The cost of extras, implied in a research instrument, is partially balanced by the cost of added stability, robust construction, explosion proofing, purging, etc., in a plant instrument. An American example of this is the infra-red gas analyser, which is very simple in principle but comparable in cost with a single-beam instrument. In general, the use of a common basic design for plant and research models might give a plant-control instrument of better performance than at present for the same cost and at the same time reduce the cost of the complete research instrument by reducing that of a basic part independently of refinements and additions.

Author's Comment

Inquiries about the ratio of cost of gas analysers to single-beam spectrometers in England does not bear out the above American example. The cost of a British single-beam spectrometer is about £2000 and of an infra-red gas analyser about £300 without accessories.

Sources, Slits, and Cells

An effort has been made to group the manufacturers' comments on component criteria in the same order as they appear in the paper, but

* Part I was published in the *Journal*, 1951, **37**, 125–34.

† " Shell " Refining and Marketing Co. Ltd.

without distinction between plant and research models. Regarding sources, it has been suggested that an aperture and mirror should be provided so that radiation can be introduced from outside the case for the examination of flames, solar spectrum, etc. Such a feature also makes possible the use of a complex auxiliary optical system, *e.g.*, residual rays, reflection cells, multiple path cells, etc. There seems general agreement that as regards the size of the source used, providing the emission is constant over a large source area, focus on the slit becomes less critical. It is the brightness of the source which matters in slit illumination; the area is of no consequence. The use of a carbon arc would necessitate a double monochromator owing to the enormous false energy produced at longer wavelengths. The suggestion that the prefocused source needs a better "plug in" fitting meets general approval, but it is pointed out that focusing on the entrance slit is best done by adjusting the appropriate mirror. It is felt that the differences between Globar and Nernst are insufficient to warrant having both sources on an interchangeable mounting. The Globar offers greater freedom from stray light at comparatively longer wavelengths, but must be water-cooled, which might be inconvenient in a mobile instrument but not insuperable. The Nernst emits more energy than the Globar at all wavelengths, but especially near the energy peak at *ca* 2 μ. On this account the Globar would be useful for reducing long wavelength stray light, but only with some sacrifice of resolution or speed of response. The Globar has a large radiating area and consequent high current consumption. The wear and tear on a Nernst is greatest during stopping and starting, and when not in use it is advised that it be left on continuously at low current (about 0·25 amps), the extra heat produced being used for maintaining the instrument at a slightly elevated temperature and reducing the risk of condensation.

Author's Comment

Deposits, presumably of sulphur from CS_2, have been noticed in the region of the Nernst on the focusing mirror and the interior of the spectrometer case. The deposit on the mirror may be avoided by a suitable baffle. As the spectrometer used by the author is continuously thermostated, any benefit from that direction gained by running the Nernst continuously would be small. The experience of the author tends to show that the effective working time (8 hr day) of a Nernst as distinct from its actual life is shortened by continuous running. The Globar lifetime is not appreciably benefited by being run at low current, and there is no suitable Globar source in this country. The statement made by one of the American manufacturers to the effect that the Nernst emits more energy at all wavelengths seems at variance with a literature reference [1] which states that the Globar is advantageous for measurements beyond 10 μ.

Slits

Passing on from sources to slits, it is found that although a case might be made for fixed slits in plant models the manufacturer seeking to standardize the slit mechanism from a cost point of view would prefer a variable slit only. In modern design they are adequately precise for the most exacting work, inexpensive, and a great convenience. Also in interchanging slits,

great accuracy of location would be necessary, since variation in slit position will cause errors in wavelength calibration. It is obviously very important in a plant instrument where densities at "spot" wavelengths have to be measured that the wavelength calibration should be accurate and reproducible.

Author's Comment

The idea of fixed slits for a plant instrument had been suggested mainly because they would appear cheaper. A recent inquiry into the price of a fixed slit for spectrographic purposes showed it to be much more expensive (*i.e.*, *ca* £25) than had been anticipated.

Cells

With regard to cells, the manufacturers agree on the need for better window material and with it a reasonable variable-space cell. Improved types of cells are being developed, including a multi-reflection gas cell. A British manufacturer in his latest radiation unit has left room for special cells, and it will accommodate 20-cm gas cells. One American manufacturer feels that the present design of continuously variable cell is too imperfect to make them reliable tools for any but the most expert workers and that they are quite unsuitable for routine work. Another American firm thinks that complete removal of cells is equally convenient for gases and liquid, that fixed cells are easier to build and maintain, and that a set of 0·1-, 0·4-, and 1·0-mm cells should suffice for ordinary work.

Author's Comment

It should be mentioned here that one of the members of the IP spectroscopic panel has designed and patented a variable-space cell which is much less massive than the commercial cells at present available. It is designed for use with a specific British instrument, and preliminary tests indicate that it will be both accurate and convenient to use.

Wavelength

The next group of comments to be considered is that dealing with wavelength, resolution, and prism interchange. One American manufacturer feels that as resolution is not a primary requirement for plant analysis, prism base and optical quality limits are not important. An arbitrary scale is considered best, as it does not restrict interchange of prisms. A non-arbitrary scale, *i.e.*, wavelength or wave number, would require, on interchange of prism material, interchange also of an accurately calibrated cam, which would be very difficult even for a skilled operator. It is also felt that direct linkage between wavelength and chart makes variable scanning speeds quite permissible. Another American manufacturer thinks that quite a lot of "backlash" can be tolerated and high reproducibility obtained, provided the setting is always approached from the same direction. However, although there is no need to sacrifice ruggedness of construction, precision mechanisms exhibit little "backlash." Also the same firm feels that speed suppression has points for and against it, inasmuch as, with intensities of weak bands only a few times the noise level, there is danger of them being skipped over.

The British point of view is that, for absolute accuracy, there should be a direct screw drive between " wavelength " drum and Littrow mirror. A linear scale facilitates accurate interpolation, but, when the utmost accuracy is not required, there is no reason why a secondary scale, directly engraved in microns, should not be available. This feature will be incorporated in a new British model. One British firm would like some indication of the importance attached by users to the provision of a linear wavelength or wave number scale.

Author's Comment

This latter point is ground on which an author fears to tread.

Resolution

Comments on resolution come mainly from American sources, and are general in nature. The prism should be quite satisfactory for industrial work, although the use of the echelle is a possibility for narrow range coverage. The prism grating combination is expensive, the range of the echellette limited, and the problem of driving prism and grating simultaneously, difficult. Mirror quality is less important in affecting resolution than is commonly believed, and several factors, *e.g.*, slit curvature, have an equal or greater influence. The suggestion is offered that the basic manochromator of the plant machine be built in such a manner that two of them in sequence could be used as a double monochromator. High resolution could then be obtained using a prism in the first and a grating in the second section.

Prism interchange is considered very simple, since usually each prism has its own mount and can be removed and replaced without disturbing the calibration. Prisms available are NaCl, KBr, LiF, CaF, and SiO_2, the angle usually being 60°, although this can be difficult to adhere to if it is undesirable to change the Littrow angle.

Detector and Amplification

Next to be considered are the detector and signal amplification. Comments on detectors come entirely from British firms. They feel that there is little to choose between the thermistor, bolometer, and thermocouple, but the bolometer seems preferable in that it does not have to be evacuated. Another suggestion on suitable detectors concerns the Golay Pneumatic cell, which is rather robust, does not require very precise condensing of radiation upon it, and by virtue of its photo-electric amplification needs only a simple electronic amplifier of which the noise characteristics are uncritical. American experience with this detector suggests that in sensitivity it is equal to or even better than their best thermocouple–transformer systems.

Author's Comments

It would be advantageous if manufacturers could supply detectors with fairly standard sensitivity so that when an existing detector needs replacing, the replacement sensitivity may not differ considerably from that of the previous one.

Amplification

Manufacturers seem to be largely in favour of A.C. amplification, one going so far as to say it is mandatory, although for time adjacent Io and I measurements D.C. amplification is possible but not attractive. It is felt that although D.C. amplifiers can have more sensitivity, this is only obtained at the sacrifice of recording speed, and drift can be a very troublesome practical difficulty which is not easily overcome. D.C. amplification systems employing a galvanometer and photo-electric relay require vibration-free conditions and a fair amount of maintenance. On the other hand, A.C. amplifiers for spectrometers have the advantage of freedom from drift, indifference to vibration, lack of maintenance problems, and ease of operation. They may be highly complicated but operate simply enough and, if properly designed and made, should give trouble-free operation over long periods. Nevertheless, a spare amplifier is a great help if the apparatus develops a serious fault.

Since one cannot separate speed and sensitivity of a detector, but one speaks of equivalent noise input at the band pass used, then the response time of a plant measurement would permit a band pass that would greatly offset the signal-to-noise loss in A.C. work.

There seems to be some contradiction between the relative cost of A.C. and D.C. amplification, a British firm maintaining that D.C. amplifiers are comparatively cheap, whilst an American manufacturer quotes $820 for an A.C. amplifier with chopping mechanism as against $795 for a D.C. amplifier alone.

Author's Comment

Many spectroscopic laboratories employ spark equipment which can cause serious disturbance to some amplifiers by radiation or through the mains. In this respect, for comparable sources of interference, D.C. amplifiers of the non-thermionic types [2, 3, 4] are less susceptible to disturbance, while A.C. amplifiers which are tuned to some harmonic or sub-harmonic of the mains frequency (to suit the convenience of the chopping system) are more likely to be susceptible.

Measurement and Recording

The next section deals with the manufacturers' comments on measurement of intensity of absorption, recording of spectra, especially on a per cent transmission basis, the interference of atmospheric bands, and the minimizing of false energy.

It has been pointed out that the null-point potentiometer is not the simplest measuring device, since a galvanometer with direct-reading scale is even simpler although less convenient and accurate than a null-point potentiometer. A British manufacturer feels that direct optical density measurements are hardly worth while, since the variation, with wavelength, of stray light must inevitably lead to error, and prefers to find the false energy at each wavelength and then make a correction when converting the apparent sample transmission to optical density.

Author's Comment

This method, though correct, is time-consuming. Direct optical density measurements are definitely attractive to commercial spectroscopists, and should be feasible if the false energy is reduced to a *negligible* minimum with a glass chopper.

Recorders

Comments on recorders come from a British firm and defend the 5-inch record as being of sufficient width. It is stated that although larger records may read more accurately, this is not justified when taken in conjunction with the other errors in infra-red spectrophotometry such as the difficulty of matching cells. Also large records which have to be long as well as wide to give reasonably proportional spectra are very unwieldy to use.

Author's Comment

When it is necessary to obtain the spectra of a sample at different dilutions it is also desirable that these should be recorded on the same chart section to facilitate filing. This is easy on a wide chart, but can be confusing on a narrow chart.

Double-Beam *v.* Memory Standardization

Most manufacturers have tactfully avoided comment on the respective merits of double-beam and memory standardization. It should be borne in mind here that firms do not necessarily produce instrumental models employing different fundamental principles because these principles have greatly differing merit. The question of prestige enters into the picture, although only scientific arguments are used when comparisons are made. A member of the panel did feel, however, that standardizing a memory instrument with an *empty* cell might involve errors due to interference. An American firm explained that " in this respect there is no difference between the double-beam and the memory-standardized instrument. Essentially the same problems arise in obtaining suitable cells and operating techniques regardless of whether the beam through the reference cell is used nearly simultaneously or at a considerably different time from the measurement beam; the only systematic difference is that with memory standardization it becomes possible to use the same cell for standardization that is used on playback. Some people have apparently concluded that it is mandatory to do so, but this, of course, is not at all true. The question might be asked as to what would be used on a double-beam instrument."

Author's Comment

An operator of a single-beam instrument who is forced to convert single-beam records to percentage transmission spectra would welcome either a memory-standardized instrument or a double-beam instrument. There seems no question of inaccuracy of wavelength calibration between the two systems, although rival claims have been made as to the accuracies of band intensities. Although an instrument accurate in wavelength and

band intensity would be ideal, one might be prepared to repeat the quantitative measurements in a single-beam instrument.

The statement that there is no commercial memory-type spectrometer yet on the market is now no longer true.

Atmospheric Bands

The elimination of atmospheric water bands and of false energy have a natural place in any discussion on accuracy of intensity measurements.

Concerning the former, one American firm feels that, in a good optical system, this is merely a question of alignment and can be achieved. Double-beam models operate without desiccation where there is strong atmospheric absorption, although the instruments become sluggish owing to loss of energy. Another American firm, whilst having no dispute with the statement that the elimination of atmospheric absorption (in any type of instrument) is best carried out by evacuation, states that background, unless extremely intense, is quite readily eliminated by the memory-standardization feature. Advice is offered here that the optics of the instrument may be protected from atmospheric humidity by thermostating at a temperature substantially higher than the highest anticipated ambient and that flushing the instrument with tank nitrogen is a useful way to remove water vapour and carbon dioxide. A British manufacturer feels that water vapour and carbon dioxide can be eliminated by activated alumina and soda asbestos, the CO_2 completely and the water vapour slowly, owing to absorption on the walls of the instrument. It should be possible to reduce water vapour to 5 per cent of its normal value without much difficulty.

Author's Comment

It has been found in practice that the introduction of dry, CO_2-free air into the spectrometer is more effective than tank nitrogen. The thought must occur that, in double-beam instruments, the use of desiccation if only to improve their responsiveness repays the slight inconvenience. It should be unnecessary to mention that the careless intrusion of organic solvent vapours should be prevented.

False Energy

False energy correction is the last but not least of the considerations of accuracy measurement. It is generally thought that false energy needs re-defining. American manufacturers reckon that most false energy essentially follows the true radiation path, *i.e.*, the energy goes through the prism, returns and scatters within the prism over a slight angular variation from its true path. A reasonable definition would be that false energy is any radiant energy to which the detecting system will respond which lies outside the desired spectral region isolated.

Unless the initial focusing is very bad, the majority of false energy *cannot* be eliminated by good focusing alone. One also needs the proper use of baffles or diaphragms in the design and the selection of optical elements of high quality throughout the monochromator. Good filter systems, however, such as the Oetgen rotating filter shutter or the White grating filter bring the false energy down to acceptable limits in a single monochromator instrument provided it is well adjusted. Since there are no

completely satisfactory filters, it should be stressed that a well-built double monochromator is the only real answer to the elimination of false energy. A British firm points out that reduction of false energy to as low a value as can be attained is well worth while. By adjustment only, figures of less than 2 per cent below 13 μ and less than 12 per cent at 15 μ are possible. By using simple expedients, *e.g.*, glass or lithium fluoride, it is possible to keep false energy down to 1 per cent for the 2 to 15 μ region.

Ultra-violet Instruments

Comment on the criteria for ultra-violet spectrometers deals mainly with the necessity for thermostating, although one American manufacturer thinks 2000 Å is low for most ultra-violet instruments. Compensating mirrors, whilst a valuable adjunct to temperature control, have the additional drawbacks of limited range, perfect compensation at only one wavelength, and hysteresis. Both British and American firms conclude that thermostating is desirable but not essential.

Author's Comment

One cannot help feeling that the peak intensity measurements of sharp bands at " spot " wavelengths on an unthermostated instrument may not be left to a semi-skilled plant operator. Also the effect of lack of temperature control on aromatic and other analyses has been reported in the literature.[5] A specific case mentioned is the 2 per cent error per ° Celsius in the ultra-violet determination of 1 : 3-butadiene in the vapour phase. Hence it would appear both desirable and essential to have the instrument thermostated and, that the temperature variation should not exceed ± 0·5° C. In conclusion, the possibility of interesting modifications in spectrometer design must be mentioned. An American firm envisages the possibility of a double monochromator on a single-beam instrument. The Savitsky[6] arrangement will be incorporated in this firm's standard accessories by 1951. British designers intend to manufacture a comparatively simple monochromator without any drive mechanism. An actuating unit providing a drive for the slits and for the wavelength screw will be available, and several types of actuating unit will be manufactured, so that the user can choose the type most suitable for this particular needs. For plant use, a very simple drive unit can be attached, while for research purposes more elaborate units will be provided, and it will be possible to bring out further units to carry out more and more complicated programmes such as may be required in the future. Cathode-ray presentation and the equivalent of turret operation will be available. In this way the spectrometer itself will not become obsolete as time goes on, but can always be brought up-to-date by fitting the most advanced type of drive unit.

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DETERMINATION OF DRY-SLUDGE CONTENT OF FUEL OILS: DEVELOPMENT OF THE SHELL HOT FILTRATION TEST (SHFT)

By W. J. VAN KERKVOORT, M.B.E.* and A. J. J. NIEUWSTAD *

SUMMARY

It has long been felt that the existing methods of determining the dry-sludge content of fuel oils do not supply reliable information. A new test has been developed in which the fuel under test is filtered, under pressure, through hardened filter paper using a specially designed apparatus.

This method involves a minimum of adsorption and flocculation of oil constituents on the filter. After filtration, filter and residue are washed with a solvent. The filter disc is weighed.

The method has proved valuable in determining the actual dry-sludge content in all kinds of fuel oils, from gas oil up to cracked residue. In combination with an accelerated storage test it provides a means of rapidly obtaining quantitative information on the sludging tendency of a fuel blend. It also simplifies the analysis of tank bottoms and centrifuge deposits.

INTRODUCTION

IN all applications, *e.g.*, in steam boilers, industrial furnaces, diesel engines, and domestic appliances, the cleanliness of the fuel is an important factor, since the presence of suspended matter may cause serious difficulties during storage and pumping and atomization in burners or injection equipment.[1, 2, 5]

In practice, the precautions taken usually involve the use of filters, settling tanks, or centrifuges. These means are effective so long as the matter separated does not affect the operation of the apparatus concerned. (For example, a filter may become fairly rapidly clogged, leading to complete interruption of the fuel supply.)

The character of such suspended matter falls into two main groups :—

(i) extraneous matter which may enter the fuel during transport or storage;

(ii) suspended matter present in the fuel during manufacture or which has been formed during storage or heating.

The former group may comprise tank scale, siliceous matter, salt (derived from seawater), and even fragments of packing or jointing material. The latter group includes " carbon " and asphaltene-like substances and also paraffin wax, which in practice should not be harmful, since it dissolves on heating and will not lead to filter clogging if the fuel is adequately preheated.

All these materials are usually collectively referred to as " sludge." As this vague term is also applied to water-fuel emulsions, it is suggested that the substances mentioned under (i) and (ii) be termed " dry sludge " and the name " wet sludge " used for water/fuel emulsions and their combinations with dry sludge.

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It is the responsibility of the fuel supplier to ensure that the materials mentioned under (i) are not in the fuel at the time of delivery, and for this purpose the "sediment by extraction" procedure [3] is an adequate check. Damage to fuel pumps and injection equipment usually only results if the customer fails to safeguard the fuel against extraneous contamination during storage.[2]

It is also necessary for the fuel supplier to restrict the presence in fuel oils of the suspended matter mentioned under (ii), and one of the objects of the present article is to give a critical review of the control methods available.

The presence of such suspended matter is closely associated with the production methods and blending techniques used, as is indicated in the following section.

Production and Blending Techniques

Distillate fuels are often blended from components which include some derived from thermal or catalytic cracking processes. Thermally cracked distillates, by reason of their more pronounced unsaturated character, have a tendency to react with atmospheric oxygen, thereby forming compounds which may dissolve only with difficulty. The solvent power of the cracked component itself, or of the mixture of components, determines whether or not such compounds will deposit from the fuel.[12]

Again, cracked residues are often incorporated in residual fuels and, if the cracking conditions have been unfavourable, may contain carbonaceous and undissolved asphaltene-like materials. The quantity of these materials may undergo changes during storage and heating of the fuel blend, depending on the nature of asphaltenes present in the residue and the composition of the asphaltene-free oily medium. These changes are associated with the colloidal structure of such residues, which is similar to that of bitumens. The stability of such systems is governed by the adsorption equilibrium between the asphaltene micelle and the oily medium and has been the subject of considerable investigation.[4]

The preparation of cracked distillates with the necessary degree of oxidation stability and cracked residues containing only peptized asphaltenes (and therefore no dry sludge) is now an established refinery technique, and results in satisfactory market grades. The preparation of a sludge-free fuel, however, not only depends upon the quality of the individual components but also on how they behave when blended together. The residual fuel components containing peptized, cracked, or straight-run asphaltenes may suffer flocculation of asphaltenes when blended with unsuitable components and consequently will deposit dry sludge. Depending upon the stability of the asphaltene/oil system and the viscosity of the fuel blend, sludge formation may commence immediately after blending or only show up after some storage or heating. The delayed formation of dry sludge can be particularly troublesome in oil fuel preparation.

One of the first requirements of a refinery is for a reliable method of assessing the presence of dry sludge in both the components and in the finished product. In addition to the usual requirements of a refinery test (*i.e.*, speed and accuracy), a dry sludge test must also eliminate as far as

possible those factors which are responsible for the delayed formation of sludge, in order that the result may not be misleading.

Brief descriptions are given below of the laboratory methods at present available for determining the amount of dry sludge present in oil fuels.

Existing Sludge Tests

The oldest method still in general use is no doubt the determination of water and sediment,[6] sometimes called B.S. & W. The attractiveness of this centrifuging method lies in the fact that it can be carried out rapidly in practically any laboratory and by unskilled staff. The criticism which can be made against it, and which is almost as old as the method itself, is that the benzene dilution may affect the original dry-sludge content. According to the nature of sludge and fuel, either the sludge can be dissolved partly or completely, or more sludge can be precipitated from the fuel. If fairly large quantities of sludge are separated a certain amount of fuel may, moreover, be entrained by the sludge, so that the method gives no reliable picture of the actual dry-sludge content. In refinery checks on the quality of a certain fuel grade which is invariably blended from the same components, the method may give some indications if considerable variations in fuel quality occur. However, the results have no absolute value in relation to fuel quality and are often quite misleading.

The sediment by extraction method,[3] in which the fuel is extracted with boiling benzene, only gives indications as to its content of " carbon " and extraneous matter, while dry sludge (flocculated asphaltenes) is sometimes dissolved in the benzene. It has, moreover, been found that a deposit of asphaltene-like materials may be formed on the outside of the extraction thimble, possibly through flocculation by locally very high dilution with benzene.[7] Hence, this method does not give a true picture of the actual quantity of dry sludge present.

Centrifuging tests, in which undiluted fuel is centrifuged, carried out at elevated temperature, suffer from the drawback that oil is entrained by the sludge, as has already been noted.

Early investigators attempted to remove the entrained oil by washing the sludge. It will be evident, however, that the choice of the correct " neutral " extractant for each sludge or fuel will raise an additional problem, and that the use of a general purpose solvent is out of the question.

An interesting approach to the problem has been described by Voskuil and Robu.[7] Dilution of the fuel under test with increasing quantities of a flocculating hydrocarbon gave rise to increasing amounts of precipitate. The actual sludge content was determined by graphical extrapolation of the precipitation curve to zero dilution. Apart from difficulties in determining the quantities of precipitate accurately, this method is too laborious to serve for checking purposes, and is to be regarded rather as a research tool.

Various investigators have recognized the drawback of previously diluting the fuel with a solvent, and have therefore tried to determine the sludge content of the undiluted fuel.[8, 9]

These investigators tried to obtain a true picture of the actual quantity of sludge present by filtering the undiluted fuel at high temperature.

The choice of filtering material is of great importance in this case, and there is a risk of the bulky asbestos filters used by them easily adsorbing oxidation products, resins, and incompletely peptized asphaltenes that may be present in the fuel. As a result, the fuels which are free from sludge according to Voskuil and Robu's method (dark-field illumination under the microscope), yet seemingly contain a considerable proportion of sludge according to the method of Hulse and Thwaites.[8] This drawback is caused by material irreversibly adsorbed on the filter material. The dry-sludge contents found by the latter method are, therefore, usually higher than the actual contents of dry sludge.

A separate group of methods, though not true sludge determination methods, is formed by the heat-stability tests, the best known of which are the Batchelder test [10] and the U.S. Navy NBTL test.[11] Both tests aim at determining the behaviour of a fuel in pre-heaters. The criterion is the quantity of sludge which has deposited on the heater tubes at the end of the test. In the Batchelder test this quantity is weighed, in the NBTL test it is assessed visually. These tests are undoubtedly very useful in evaluating a fuel in practice. However, they do not supply all the information required in the refinery. One drawback is that they do not indicate whether the sludge deposited on the heater tubes was already present in the fuel before the test was started, or whether it was formed during the test.

This may be of importance in tracing the cause of the sludge deposition. Further, these tests give no information about the behaviour of the fuel, for instance, during centrifuging, where the quantity of actual sludge must be known and not the quantity of potential sludge as given by the heater tests.

The foregoing shows that if fuel components and fuel blending are checked by the above methods, most of which give only relative figures, the production of sludge-free fuels is largely a question of experience.

These methods are for the most part not accurate enough, and they are, for instance, unsuitable for predicting the quantity of dry sludge which will be separated in centrifuges.

It is particularly this latter defect which has given rise to the development of the new test described below.

Shell Hot Filtration Test *

A method has been searched for which would be capable of effecting a very sharp separation between oil and dry sludge, and which would therefore enable the separated sludge to be washed without involving the risk of dissolved asphaltenes being precipitated from the oil entrained with the sludge. The sharpest separation is obtained by filtration, the rate of which can be increased by using air- or nitrogen-pressure. The filter material must be such that oxidation products, resins, and rather poorly peptized asphaltenes will be adsorbed to only the slightest possible extent. For this purpose hardened filter paper (Whatman No. 50, diam 55 mm) was chosen. In order that the filter paper might be suitable for

* This name has been chosen in order to avoid confusion with existing methods of similar denomination.

filtrations under a pressure of 4 to 5 kg/cm² (= 60–70 p.s.i.) this paper had to be placed on a flexible base, for which felt was used. This felt disc rests on a perforated plate with a flat, raised edge. This ensures that during filtration the felt disc together with the filter paper lying on it

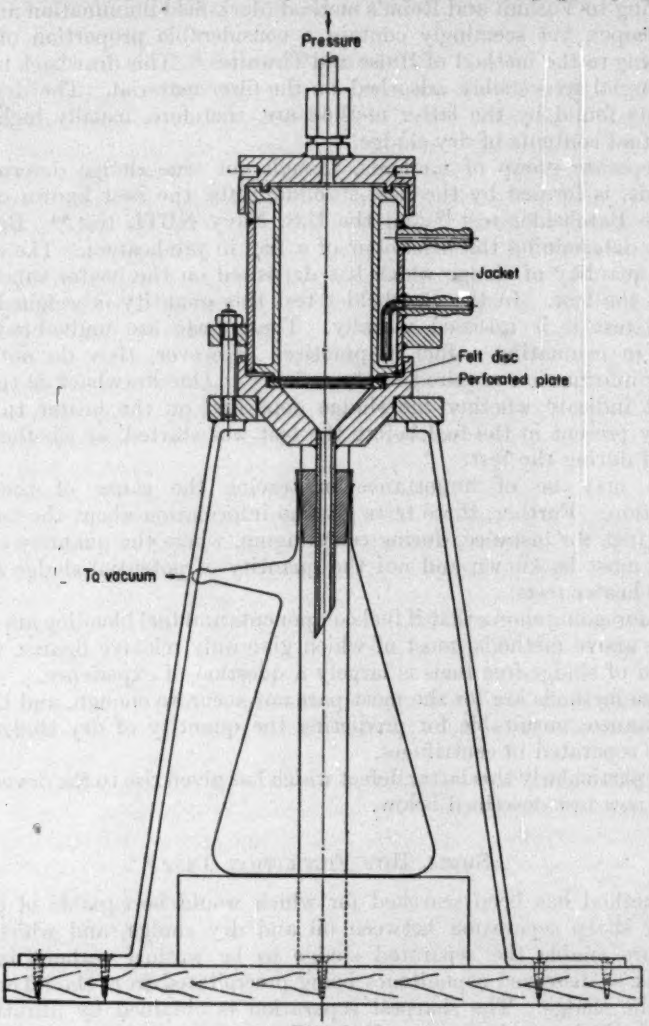

FIG. 1

is slightly depressed in the middle, so that the last few drops of oil to be filtered go to the centre of the filter, and are forced through it by the air or nitrogen current applied. In the case of low-viscosity fuels this filtration test is carried out at any appropriate temperature for which the rate of filtration is considered satisfactory, and in the case of high-viscosity fuels at 100° C.

To make filtration at high temperature possible, the filter is surrounded by a jacket through which steam or water of the required temperature can be circulated.

Assembly and lay-out of the apparatus are shown in Fig. 1.

Procedure

For High-viscosity Fuels

Dry the filter papers for 1 hour in a drying oven at about 105° C, and store them in a glass container with ground-in stopper. For analysis weigh one filter in a weighing bottle. In view of the hygroscopicity of dried filter paper, the use of desiccators without a desiccant and placed in the immediate vicinity of the balance is recommended, and it is advisable to make use of a damped balance. In moderate climates sufficient accuracy has been obtained by weighing the filter paper directly on the pan of the balance immediately it comes from the drying oven, *i.e.*, while still hot.

After the heating jacket has been removed, place a felt disc on the perforated plate, connect the vacuum flask to the vacuum line, and place the weighed filter paper on the felt disc. The vacuum ensures that the filter paper is kept in its proper position. Screw the heating jacket on its counterpart, and pass through live steam after closing the vacuum line to avoid excessive cooling of the filter.

Place on the filter about 10 g (accurate to 100 mg) of the fuel under test, rapidly preheated in a glass container to 100° C, ensuring that no fuel runs along the metal wall, open the vacuum cock, screw on the cover, and apply air or nitrogen pressure.

Continue the filtration until air or nitrogen flows through the filter, indicating that filtration is nearly complete. After unscrewing the cover, inspect the filter, and if it is practically dry, pass cooling water through the heating jacket. After the filter has been cooled, wash the filter paper first with 5 ml of *n*-heptane and then lavishly with an ample supply of the same solvent, and suck the liquid into the flask, applying vacuum. Remove the heating jacket. Any oil that is still present on the rim where this jacket rested on the filter paper, should be washed away with *n*-heptane. Remove the filter paper, dry and weigh it in the same manner as used in preparing the filter paper before the test. Express the results of the test in per cent by weight, taking the mean value of two determinations which shall not differ by more than 0·05 per cent.

Low-viscosity fuels (*e.g.*, gas oils and conventional diesel fuels) may be examined at temperatures corresponding with those at which the fuel is normally handled in practice.

Some Results Obtained with the New Test Method

To illustrate the value of the SHFT method some fuels were blended in the laboratory and examined with the results shown in Tables I to V.

Discussion

The results in Tables I to V show that the SHFT method can be used in a very extensive range of applications. From the tests on the experimental blends A and B it follows that the water and sediment test and the sediment by extraction test give no information on the actual sludge

TABLE I

Comparison of Results of the SHFT method with other Methods

Experimental blend A consisting of 50 per cent by wt of straight-run fuel oil with 50 per cent by wt of cracked residue.
Viscosity Redwood I at 100° F : 1535 sec.

Test method	Blend before heating	Blend after 24 hr heating at 100° C
Water and sediment, % vol . . .	0·1	0·15
Sediment by extraction, % wt . .	0·02	0·03
SHFT at 100° C, % wt	0·30	0·70

Experimental blend B consisting of 25 per cent by wt of straight-run fuel oil with 75 per cent by wt of cracked residue.
Viscosity Redwood I at 100° F : 1510 sec.

Test method	Blend before heating	Blend after 10 day heating at 100° C
Water and sediment, % vol . . .	0·35	0·9
Sediment by extraction, % wt . .	0·07	0·09
SHFT at 100° C, % wt	0·68	0·35

TABLE II

Example of Incompatibility of Fuel Blending Components

Experimental blend C.
Viscosity Redwood I at 100° F : 1560 sec.

Blending component	% wt in blend	SHFT (100° C) % wt of component		SHFT (100° C) % wt of blend	
		Before heating	After 24 hr at 100° C	Before heating	After 24 hr at 100° C
Straight-run waxy fuel oil .	26	0·02	0·03	} 0·35	} 0·50
Straight-run asphaltic fuel oil .	25	0·03	0·02		
Cracked residue . . .	49	0·04	0·06		

TABLE III

Comparison of the Results of the SHFT (100° C) with the Amounts of Sludge Obtained on Centrifuging in the De Laval Separators (Purifier and Clarifier in Series) at 85° C

Type of fuel	Viscosity Redwood I (100° F, sec	Sludge removed calculated from SHFT (100° C) results before and after centrifuging, % wt on fuel	Water-free sludge in centrifuge bowls, % wt on fuel
Straight-run Middle East oil	350	0·02	0·015
Commercial blend containing cracked residue .	1520	0·02	0·01
Experimental blend D .	1071	1·09	0·79
Experimental blend E .	1175	0·98	0·99
Experimental blend F .	3540	0·24	0·21

TABLE IV

Comparison of the Res lts of the SHFT (100° C) with those of the U.S. Navy NBTL Heater Test

Type of fuel	Viscosity Redwood I at 100° F, sec	SHFT (100° C) before heating, % wt on fuel	SHFT (100° C) after 24 hr at 100° C, % wt on fuel	SHFT (100° C) after NBTL test, % wt fuel	NBTL rating
Experimental blend G	3160	0·02	0·03	0·05	Stable No. 1
Experimental blend H	3250	0·14	0·34	0·31	Borderline No. 2
Experimental blend K	6410	0·16	0·10	0·15	Stable No. 1

TABLE V

Dry-sludge Content of Cracked Residue

Residue of test run. Dubbs Thermal Cracking Unit.
Viscosity Redwood I at 100° F: 24,500 sec.
SHFT (100° C): 0·04% wt.

content of a fuel, nor on the behaviour of a fuel during heating. The data supplied by the SHFT (100° C) carried out before and after prolonged heating clearly indicate that additional sludge may be formed or that sludge originally present may go into solution.

These changes are associated with changes in the adsorption equilibria between asphaltene micelles and oily medium. This equilibrium may undergo considerable shifts if a cracked residue is blended with fairly large quantities of aliphatic components. In particular cases this point may lead to the formation of dry sludge, which phenomenon is referred to as "incompatibility of components." The experiment on blend C exemplifies this fact. Whereas the components of this fuel are free from dry sludge, and remain so on heating, the mixture does show dry-sludge formation. As colloidal adsorption equilibria are established only slowly, more dry sludge has been formed after 24 hours heating at 100° C.

The SHFT has proved particularly useful to predict the quantities of sludge that will be separated in centrifuges. As the sludge found in this test is free from water, its results can only be compared with the quantities of water-free sludge from centrifuge bowls. Though filtration and centrifuging are fundamentally different methods of separation, the results obtained (Table III) show that there is a reasonable correlation between the quantities of dry sludge removed by the SHFT and the centrifuge. On the whole, the separation between oil and sludge will be somewhat less sharp in the centrifuge than in filtration, due to some entrainment of oil by the sludge. This phenomenon will be more pronounced if the throughput of the centrifuge increases, so that in these cases slightly more oil will be entrained by the sludge separated in the centrifuge.

The SHFT sludge content of a fuel before and that after centrifuging will at the same time give information about the efficiency of the centrifuging units in use.

In the discussion of the results obtained with blends A and B it has already been pointed out that the SHFT can be used to study the be-

haviour of fuels on heating. Though the SHFT is not a stability test, it can be used as such in combination with an ageing procedure.

In Table IV the SHFT results of a fuel before and after heating at 100° C for 24 hours are compared with those of the U.S. Navy NBTL heater test. The data show that the "borderline stability" found in the NBTL test is clearly reflected in the SHFT results.

In this connexion, the SHFT has the advantage that it allows of determining whether the sludge deposited on the NBTL tube had originally been present in the fuel, or whether it has been formed during the test.

Though even very viscous residues can be examined by the SHFT (see Table V), some fuels filter with difficulty. Centrifuge experiments and microscopical examination have shown that, in this case, not the quantity but the nature of the sludge plays a rôle.

During the development of the test, attention was paid to the possibility that the dry-sludge content might undergo changes when heated at 100° C and during filtration. Microscopical examination and SHFT determinations after heating at 100° C for 1 and 2 hours showed that the differences in dry-sludge content are negligible. Dependent on the fuel viscosity and the texture of the dry sludge, a filtration can be carried out in a period ranging between 5 and 60 minutes.

On the ground of the experience already obtained the repeatability of the SHFT can be put at 0·03 per cent by weight between any two tests on the same fuel.

The SHFT apparatus has proved to be very useful in examining tank bottoms, centrifuge sludges, etc. The ordinary filtrations necessary to determine what portions of a sludge are soluble in various solvents take much more time than the SHFT, while the latter can be carried out at any desired temperature. In addition, the deposit and the filter can be washed much quicker.

Acknowledgment

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Oilfield Exploration and Exploitation

Geology

2006. Characteristics of crude oils currently produced in the United States. H. M. Smith. *Oil Gas J.*, 29.3.51, **49** (47), 308.—Certain characteristics of the crude oils produced in the oil-producing areas of the U.S.A., based on the U.S. Bureau of Mines routine analysis are discussed. The oil-producing areas have been divided into eight geographical regions, and 330 crudes are considered. C. A. F.

2007. Foraminifera of "Multicoloured Eocene" and its paleogeography in the region Sanok–Gorlice. J. Czernikowski. *Nafta*, May 1950, **6**, 118–22.—In 1895 J. Grzybowski attempted a limited estimation of the age of the "multicoloured Eocene" in this region. Scarcity of fossils was the reason for many errors, and now the author describes the formation as belonging to Palæocene in the main and to the early Eocene. A map of the district, four tables of fossils, and two others are given. M. S.

2008. Thermal conditions of formation of petroleum deposits. (From S. N. Obriadchikov, *Neft. Khoz.* 3 & 4, 1946.) I. Niementowska. *Nafta*, Apr. 1950, **6**, 100–2.—Chemical composition of crude oil depends in the first instance on the temp at which it was formed. Crude could have formed at temp within very wide limits—from below

150° C in presence of silicates of aluminium as catalyst to over 300° C. These conditions give rise to two different types of crudes, namely that formed at low temperature, which has little of aromatics, contains six-membered *cyclo*paraffins and light paraffins of branched-chain structure while that formed at relatively high temp is rich in aromatics, has few *cyclo*paraffins, mainly five-membered rings, and contains mostly straight-chain paraffins. The actual composition indicates the temp of formation of the crude. M. S.

2009. North Dakota strike. P. C. Ingalls. *Oil Gas J.*, 12.4.51, **49** (49), 69.—1 Clarence Iverson, Williams County, North Dakota, on test flowed approx 307 brl of 53° to 55° oil on a 17-hr test from 11,630 to 11,660 ft from acidized Devonian limestone; a gas flow of 5 to 6 million cu. ft. was indicated. This is the first commercial oil well in North Dakota. C. A. F.

2010. South Louisiana. Anon. *Oil Gas J.*, 1.3.51, **49** (43), 107.—2 V. J. Gianellon, East Baton Rouge Parish, flowed 250 b.d. of 42·5° oil from 9701 to 9706 ft. C. A. F.

2011. Chacahoula gets new pay. Anon. *Oil Gas J.*, 1.3.51, **49** (43), 31.—2 Levert Morvant in the old Chacahoula field, Lafourche Parish, Louisiana, flowed 251 brl of 29° oil in 12 hr with G.O.R. of 1790 : 1 from 14,145 to 14,160 ft. The Chacahoula salt dome was located by refraction shooting in 1926, and commercial production was found in 1938. Ten Miocene reservoirs have been developed. C. A. F.

2012. Well blows out. L. S. McCaslin. *Oil Gas J.*, 8.3.51, **49** (44), 50.—A wildcat in Stone County, Mississippi, found gas at 20,300 ft. A bottom-hole pressire of 9000 p.s.i. was indicated. C. A. F.

2013. Orderly water-flood programme for Mid-Burbank Unit, Osage County, Oklahoma. K. B. Barnes. *Oil Gas J.*, 15.3.51, **49** (45), 78.—The Mid-Burbank field in Osage County, Oklahoma, is to be systematically water-flooded; the field, which has been unitized, lies between the North Burbank and South Burbank units. Pilot floods are operating in North Burbank, and the flooding of South Burbank is being considered. All three fields have been repressured with gas for a number of years.

The Mid-Burbank field produces from the Burbank sand bar, and the first producer was completed in 1934. Cumulative production of the area to July 1950 was 5,778,130 brl, or 184 brl/acre/ft.

It is estimated that a max of 60% of the pore volume of the sand will be flooded by injected water, and at a daily injection rate of 15,000 brl water, the "free gas" space is expected to be filled in two years.

Reservoir data are included. C. A. F.

2014. Rocky Mountain gas discovered in Uinta. Anon. *Oil Gas J.*, 31.5.51, **50** (4), 67.—A well, 18 miles southwest of West Douglas Creek, Oklahoma, on the northeastern flank of the Uinta Basin, flowed an estimated 3500 M.c.f. gas/day from a total depth of 2495 ft from an Upper Cretaceous Mesaverde sand. C. A. F.

2015. Williston Basin test. Anon. *Oil Gas J.*, 17.5.51, **50** (2), 67.—Deep tests are to be drilled in the Pine area on the Baker–Glendive anticline on the western edge of the Williston Basin in eastern Montana, and in the Rickey area in Dawson County.

The Baker–Glendive anticline is asymmetrical and trends northwest–southeast for over 115 miles. The structure overlies a pre-Cambrian fault scarp. Several shallow gas fields have been found along the axis on low-relief domes. Of four deep wells drilled on the anticline, two have produced 29·5° oil from the Palæozoic. C. A. F.

2016. Rockies stature grows. P. C. Ingalls. *Oil Gas J.*, 8.3.51, **49** (44), 127.—A rapid increase in the demand for crude from the Rocky Mountain area during the last ten years has stimulated exploration for new fields in this area. In the Sussex–Meadow Creek area on the southwestern edge of the Powder River basin production has been found in the Cretaceous Sussex, Shannon, Frontier, and Lakota sands, and six pools are under development. In Converse County 35° to 40° oil is being produced

from the Cretaceous, Dakota, and Muddy. There are good oil prospects in the Beaver Creek–Lakota gas field in Fremont County. The discovery well of the Slick Creek field in 1950 flowed over 1000 b.d. of 33·5° oil from the Permian phosphoria at about 10,500 ft, and a second well 1½ miles to the east of the discovery was also completed for over 1000 b.d.

In the Far Corners region the Suan Juan basin has good oil possibilities in the Palæozoic and Mesozoic wedge outs. C. A. F.

2017. Active area. R. F. Carlson. *Oil Gas J.*, 21.6.51, **50** (7), 149.—Approx 275 wells have been completed for production from the Spraberry sand, which follows a north–south trend across four counties in the Midland area, Texas. Present activity is centred in Midland County, in which is the Tex Harvey field, the largest producing from the Spraberry. C. A. F.

2018. North Texas. Anon. *Oil Gas J.*, 1.3.51, **49** (43), 107.—1 Dolly Anderson, in the Sandusky area, Grayson County, was completed for 750 b.d. from the Oil Creek at 7157 to 7182 ft. C. A. F.

2019. Wyoming's Nugget. P. C. Ingalls. *Oil Gas J.*, 19.4.51, **49** (50), 269.—The Tip Top well in Wyoming on test flowed oil and gas from the Jurassic Nugget sand at 9682 ft. This is the first oil discovery below the Upper Cretaceous on the edge of the overthrust belt forming the western limit of the Green River Basin. C. A. F.

2020. Eager Beaver Creek. P. C. Ingalls. *Oil Gas J.*, 5.4.51, **49** (48), 129.—The Beaver Creek field in Fremont County, Wyoming, was discovered in 1938, and development commenced in 1944. Nine wells have been drilled which produce wet gas from Cretaceous, Frontier, Muddy, and Lakota sands. In 1948 45° oil was found in a deep test in Pennsylvanian Tensleep at 10,442 ft, and oil has been found in the Cretaceous Mesaverde.

The structure is anticlinal, with the axis trending north to south at surface and northwest–southeast at depth, paralleling the edge of the Wind River Basin. C. A. F.

2021. Canada. Anon. *Oil Gas J.*, 21.6.51, **50** (7), 359.—1, LSD 9,31–53–21w4, in central Alberta, on tests of the Viking sand at 2635 to 2695 ft flowed over 3 million cu. ft. gas/day. C. A. F.

2022. Long search rewarded. Anon. *Oil Gas J.*, 7.6.51, **50** (5), 62.—Texaco–Wizard Lake 2, 5 miles southwest of Leduc, Alberta, on test flowed over 200 brl/hr of 36° oil from the D_2 with G.O.R. approx 500 : 1. A thick oil-bearing section of D_3 and Viking gas were also found. C. A. F.

2023. Y.P.F. makes discovery. Anon. *Oil Gas J.*, 19.4.51, **49** (50), 140.—Campo Duran 6, 40 km northeast of Tortugal, Argentina, flowed about 1130 b.d. of light condensate with 17 million cu. ft. of gas from a sand at about 9000 ft. Total depth was approx 12,800 ft. Several wells previously drilled in the area were dry. C. A. F.

2024. Brazilian discovery. Anon. *Oil Gas J.*, 1.3.51, **49** (43), 34.—A wildcat at Almas, 4½ km east of the Candeias field, Bahia, Brazil, is reported to have flowed on test 1000 b.d. at 3770 ft from a 56-ft Sergi sand section.

A wildcat at Agua Grandel flowed 300 b.d. from 4250 ft. C. A. F.

2025. Colombian activity. Anon. *Oil Gas J.*, 19.5.51, **49** (50), 141.—Liberalization of oil legislation has stimulated exploration in Colombia. A well is being drilled in the Sinu River area to test shallow sands. Twelve wells previously drilled in the area found some production of 50° oil between 1203 and 2217 ft. Wildcats are being drilled at Balsamo, and in the Magangue area. C. A. F.

2026. Tetuan wildcat finds oil. Anon. *Oil Gas J.*, 7.6.51, **50** (5), 68.—1 Ortega in the Upper Magdalena Valley, Colombia, on test produced 200 to 300 b.d. of 29° plus-oil from approx 5800 ft. Development of the Velasquez field is being continued. C. A. F.

2027. Pemex's Macuspana Basin strike. P. C. Ingalls. *Oil Gas J.*, 10.5.51, **50** (1), 171.—1 José Colomo in the Macuspana–Campeche Basin in Mexico is producing 240 b.d. of 45° oil and 5 million cu. ft. of gas from the Lower Miocene–Upper Amate from 5203 to 5240 ft.

The well was sited on a seismic structure in a swamp region. Oil is being transported by barge by river to Frontera and to the refinery at Minatitlan.

Seismic work in the area commenced in 1950 after regional studies and gravity surveys. C. A. F.

2028. Good discovery. Anon. *Oil Gas J.*, 14.6.51, **50** (6), 65.—The East Soto well, approx 15 km northwest of Nipa, Anzoategui, Venezuela, has been completed as a dual producer for approx 400 b.d. of 21° oil from an upper sand and approx 500 b.d. of 34° oil from a lower. Pays are at approx 10,000 ft. C. A. F.

2029. Offshore well. Anon. *Oil Gas J.*, 19.4.51, **49** (50), 140.—A well drilled directionally into the seaward extension of the Guapo field, Trinidad, found flowing production from the Miocene Cruse pay at 2250 to 2580 ft and at a horizontal seaward displacement of 430 ft from low-water mark. Total depth of the well was 3300 ft. C. A. F.

2030. Offshore oil. Anon. *Oil Gas J.*, 14.6.51, **50** (6), 68.—1 Safaniya, an offshore well south of Ras Al Misha Ab on the western side of the Persian Gulf, found oil reported as 24° in Middle Cretaceous sand equivalent to the producing formation at Burghan. Jurassic zones are to be tested.

The well is in 19 ft of water, 3 miles offshore. C. A. F.

2031. Neutral Zone test fails. Anon. *Oil Gas J.*, 5.4.51, **49** (48), 68.—Fuwaris 1, the fourth test in the Neutral Zone between Saudi Arabia and Kuwait, was abandoned at approx 9400 ft.

Reflection seismic work is being carried out. C. A. F.

2032. Aramco wildcat. Anon. *Oil Gas J.*, 31.5.51, **50** (4), 69.—A well approx 40 miles south of the Ain Dar field in Saudi Arabia has been completed for production in the Arab D zone. On test 30·5° oil was produced from approx 6900 ft. A second well is to be drilled in the area.

Aramco is currently producing approx 700,000 b.d. from Abqaiq, Dammam, Ain Dar, and Qatif. Ain Dar was discovered in 1948, and produces approx 34° oil. C. A. F.

2033. Aerial photography in petroleum and mineral prospecting. A. A. Fitch, D. F. Christie, W. E. Johnstone, and G. Whittle. *Proc. Fourth Empire Min. Metall. Congr*, 1950, **1**, 219–47.—The use of aerial photography in exploration is discussed, and examples of geological reconnaissance mapping presented. G. S.

2034. New exploratory tool. P. C. Ingalls. *Oil Gas J.*, 31.5.51, **50** (4), 145.—The uses are described of a new well-logging instrument which records the magnetic susceptibility of well formations. The instrument was designed primarily to verify the concept that residual magnetic variations observed at the surface in magnetometer surveys are due either to basement relief or variations in the distribution of magnetic materials above the basement. The apparatus has verified this, and it has been found that its sensitivity is such that detailed correlations of thick shale sections can be made, and in certain areas porous zones may be delineated by using powdered iron in the drilling mud. C. A. F.

Drilling

2035. The freeing of drilling string frozen in limestone formation by pumping in of hydrochloric acid. Z. Onyszkiewicz. *Nafta*, Apr. 1950, **6**, 104.—Taken from reports of the Société Cherifierme de Pétrole, procedure adopted in the freeing of the string caught at the depth of 857 m is described. 5000 litres of commercial acid were used in a diluted state. After some 50 hr the string was freed. The acid did not affect the

casing and string, but author suggests that other fluid, *e.g.*, the crude oil, should have been tried before acid was used. M. S.

2036. Hardening of drilling tools. E. Bryjak. *Nafta*, Apr. 1950, **6**, 82–8; May 1950, **6**, 122–5.—Due to excessive wear on bits and other parts of drilling tools their performance has to be improved by providing them with a hardened layer of special material. Although the process of hardening is similar in appearance to welding, it is sufficiently different to warrant this short instructive paper. Special steels, "stellites," and granulated carbides are in use. Lists are given of all three kinds of materials, and photographs and sketches of electrodes and burners and instructions for hardening and repair of tools are also given. M. S.

2037. The application of auger and core drilling in petroleum exploration. N. J. M. Taverne. *Proc. Fourth Empire Min. Metall. Congr.*, 1950, **1**, 520–41.—Auger drilling has been successfully applied in the search for suitable oil structures in dense jungle areas. Where this method or geophysical methods fail core drilling is still being applied. Core drilling is also used to confirm faults located by seismic work. Examples of augering and coring methods are given. G. S.

2038. Modified mono-electrodes for improved resistivity logging. G. V. Keller. *Producers' Monthly*, July 1950, **14** (9), 13.—Experiments conducted on a laboratory scale indicated the possible quantitative estimation of reservoir rock characteristics, but conditions in the Bradford Field prevented the successful field application of the initial lab methods. Subsequent research was then continued in the development of an electric logging system having the advantage of variable logging depth and also of the ability to measure the resistivity of thin sections. The shielded mono-electrode consists of a single cylindrical electrode between two longer electrodes: the longer these electrodes the greater the extent of the sampling depth.

Although field tests have not been extensive, the available information would indicate a greater sensitivity in detecting thin beds.

Calibration graphs and lab results are presented. A. J. H.

2039. Continuous flow high temperature viscometer for drilling muds. R. W. Hoeppel. *Rev. sci. Instrum.*, 1951, **22**, 248–53.—This viscometer consists of a rubber squeeze pump which circulates fluid at 400 ml/min in a closed circuit through 12 ft of ¼-inch tubing. The visc is indicated by the differential pressure across the tube (ends); and gel strength by the differential pressure necessary to start movement in the tube. The circuit contains a stirrer for pre-mixing the fluid, with a valve for admitting solids or liquids, and an electrical device for detecting fluid movement when measuring gel strength. For thick fluids ⅔ of the tubing can be by-passed. For temps above 180° F the system is closed and operated at 17 p.s.i. air pressure.

Details of the pump construction are given.

The viscometer has the following advantages: (1) Only 400 ml of fluid are required; (2) abrasive fluids up to $\eta = 200$ c.p.s. can be circulated at const rate in streamline flow; (3) permits measurements up to 250° F; (4) is sturdy and requires little maintenance.

Comparative evaluation of twenty-two aqueous drilling muds was made on this and the Stormer viscometer. Some differences were noted, due to the different characteristics of the two instruments. Data on a Gulf Coast drilling mud at temps up to 250° F are given. The instrument should be useful for: (1) study of chemical treatment of hot fluids under field conditions; (2) variation of η with age of fluid; (3) determination of gel strength at hole temps of muds; (4) effect of temp on rheological properties of muds; (5) determination of basic constants for predicting pump pressures developed in the field. H. C. E.

2040. Influence of an addition of sodium silicate to drilling muds on consolidation of well walls. Z. Onyszkiewicz. *Nafta*, Apr. 1950, **6**, 102–4.—Addition of sodium silicate $(Na_2O)_nSiO_2$ improves all kinds of drilling mud tremendously. Author gives instances where addition of sodium silicate could have prevented serious breakdowns and losses. No other substance acts like sodium silicate, but it is an expensive product. (From work of Debregeas and experiments in French Morocco.) M. S.

Production

2041. Leakage of crude between cylinder walls and the piston of a well-bottom pump. (From M. I. Bazanov. *Neft. Khoz.*, 1946, **5**) translated by H. Gorka. *Nafta*, Apr. 1950, **6**, 137–8.—Due to wear on well-bottom pumps these soon develop leakages which lower their volumetric efficiency by vol $Q = \frac{\pi p}{8\mu l_1}\left[(R^4 - r^4) - \frac{(R^2 - r^2)^2}{\ln R - \ln r}\right]$ per stroke,

where p = weight acting on piston;
μ = abs viscosity of crude;
l_1 = length of piston;
R = radius of cylinder;
r = radius of piston.

A sketch and a graph are given. M. S.

2042. Pressure temperature and gas contents in oil reservoir rocks. (From paper by A. Mayer-Gürra, *Oël u. Kohle* (7), 1944.) Z. Onyszkiewicz. *Nafta*, Mar. 1950, **6**, 71–6.—Due to its temp, pressure, and gas contents crude oil underground is dissimilar to the same oil on the surface. Dealing with pressure it was observed that in non-porous rocks the pressure of oil is generally higher and in porous rocks it is equal to the hydrostatic pressure of a column of water of appropriate length (= depth).

Temp varies with depth about 1° C/33 m. Other influencing factors are conductivity of formation and second differential derivative of its sectional curve.

When crude oil is produced pressure in formation falls and causes fall of temp. This in turn lowers solubility of many paraffins and in U.S.S.R. gases are burnt in the rock to raise the temp to produce more paraffinic crudes.

Apart from being affected by temp and pressure gas content of crude depends on the nature of the gas, *e.g.*, CO_2 is three times as soluble as natural gas, and the exact solubility of this depends on its composition, the heavier hydrocarbons being more soluble. Analysis of gases dissolved in crude at the bottom of the well will give an indication of the well-bottom pressure or temperature. If it is desired to produce gas or to utilize the fact that production of crude is helped by gas dissolved in it, the reservoir should not be tapped at its lowest point. Gas often forms caps, and its solution in crude is saturated only immediately below this cap. With production pressure falls and as saturation pressure (at well-bottom temp) is reached for various gases these separate. This in turn may change the solubility of the remaining gases. Henry's and Dalton's Laws do not appear to apply.

Paper is illustrated with seven graphs and one table. M. S.

2043. Special considerations in predicting reservoir performance of highly volatile type oil reservoirs. A. B. Cook, G. B. Spencer, and F. P. Bobrowski. *Petrol. Tech.*, Feb. 1951, **3** (2), *A.I.M.M.E. Tech. Paper No.* 3017, 37–46.—Methods of calculating the volume and composition of hydrocarbon liquid condensed from the produced solution gas that has been liberated in a reservoir are presented. Laboratory data on reservoir-oil samples from the Elk City field and on another highly volatile reservoir oil were used to show that a large part of the recoverable hydrocarbon liquid from a highly volatile oil reservoir produced by solution-gas drive is obtained from the gas-phase fluid entering the producing wells. The calculations show that 18 to 26% of the ultimate stock-tank oil recovered from the hypothetical reservoirs containing oil of the Elk City field type will be condensate, and about 78% of the stock tank liquid recovered from a reservoir containing the other type of oil will be condensate. Processing the produced gas in a gasoline plant would increase the hydrocarbon liquid recoveries in the form of LPG products by 50 to 100%.

Theoretical and experimental results are presented to show that the gas-phase behaviour in the reservoir can be duplicated in the laboratory, for the declining pressure range in which retrograde condensation occurs, by either the differential or flash liberation. G. D. H.

2044. Helium tracer-gas studies in the Cabin Creek, W. Va., oil and gas field. E. M. Frost. *Producers' Monthly*, Sept. 1950, **14** (11), 36; Oct. 1950, **14** (12), 31; Nov. 1950, **15** (1), 39; Dec. 1950, **15** (2), 29.—The use of helium continues to show great promise in the study of gas movement in sands. The principle does not depend on

the absolute presence or absence of the element, but on the relative concentrations at different points in the system; since the development of a highly sensitive apparatus for the detection of He, no natural gas has been found which does not contain any trace. The use of helium is advantageous, since the element is chemically inert, and its solubility in water is less than for any other gas; although no definite data are available, it would appear also to be at most only slightly soluble in oil.

The plotting of helium content versus time assists in estimating the direction and rate of travel of the natural gas, the volume of injected gas being produced at the wells, and the nature of the transition from natural to injected gas. In order to obtain a representative set of data, the injection of helium was varied:—

Test 1, 1% by vol over a period of a week.
Test 2, 5% by vol over a period of four days.
Test 3, Slug injection of essentially pure helium.

Test 1. A general survey of the field is given. The injected gas was found to have an average content of 0·035% by volume, which was increased for the purposes of the test to 1·01%. Details are given of the location of the input well in relation to the producing wells. Helium tests conducted on wells in the vicinity of the injected well showed a variation in initial content from 0·014 to 0·040%; it has been observed that over a period of time, some adjacent wells of varying helium content have shown no tendency to approach a common concentration.

The practical results of Test 1 are compared with the theoretical analysis according to Muskat's equation of flow. It is assumed that, since the flowing fluids are part gas and part liquid, no appreciable change in density occurs, and the fluids are therefore compared to a liquid. Although general agreement is shown, no explanation has been given for the differences between the tracer studies and studies on a potentiometric model.

Mathematically, the knowledge of the initial and produced helium concentrations and the quantities of injected and produced gas should permit the estimation of formation gas. On this basis the distribution of the tracer-laden gas, relative to the injection well, is represented graphically. It was estimated that at the end of 140 days 78·7% of the tracer-laden gas had been produced; by extrapolation, it was concluded that small quantities of the injected gas would continue to be produced for six months after an injection period of one week.

Test 2. An average injected helium concentration of 4·78% by volume was maintained over a period of four days. As opposed to a system of daily averaging, as in Test 1, the cumulative production was estimated by graphical integration on time–helium content curves. The analysis was essentially the same as for the first test.

Test 3. Approx the same amount of helium was injected as in Test 1, but in this case the natural gas supply was stopped, and the helium introduced as a slug. Practically no discontinuity occurred in the injection of gas into the reservoir. Similar effects were observed as in the other test; any variation due to the difference in physical properties of the helium were discounted owing to the small amount used. The analysis varies only slightly from the previous two tests.

A discussion of the results summarizes the conclusions of the three tests; it is stated that where the time required for the tracer to reach the producing well is much greater than the injection time, then little emphasis need be put on the intensity of injection, whether 1% for 10 days or 10% for one day.

References and extensive data are given in the complete series. A. J. H.

2045. Secondary recovery of oil by air and gas injection in the Brenneman Field, Hancock County, W. Va. E. M. Tignor, W. N. Nabors, T. Jennings, and L. Krause. *Producers' Monthly*, Sept. 1950, **14** (11), 28.—Production from the Berea sandstone at a depth of 750 ft was first obtained from a well producing 200 b.d., but the field was abandoned in 1923, when cumulative production of 705,000 brl had been reached, and when the annual production was less than 1000 brl. Secondary recovery was commenced in 1927, and it is estimated that approx 375,000 brl of oil will be produced as a result of the current gas-injection programme.

A full report is given of the operations, which are considered to be the more successful in the Appalachian area. It is suggested that successful water flooding may yield a further 463,000 brl of oil.

References. A. J. H.

2046. Laboratory measurements of relative permeability. J. S. Osoba, J. G. Richardson, J. K. Kerver, J. A. Hafford, and P. M. Blair. *Petrol. Tech.*, Feb. 1951, **3** (2), *A.I.M.M.E. Tech. Paper No.* 3020, 47–56.—Laboratory measurements of relative permeabilities to oil and gas on small-core samples have been made by the "Penn State," "single-core dynamic," "gas drive," "stationary liquid," and the "Hassler" techniques. The influence of boundary effects, hysteresis, and rate has been studied. In those methods, in which the results are subject to error because of the boundary effect, the error may be minimized by using high rates of flow. In the absence of boundary effects the relative permeabilities were independent of the rates of flow. Since relative permeability is not a unique function of saturation because of hysteresis, care must be taken that laboratory measurements are made under conditions wherein each saturation is approached in the desired manner. All the five methods gave essentially the same values of relative permeability to gas, except in the region of the equilibrium gas saturation, where the stationary liquid method generally gave the lower values. For oil relative permeabilities the Penn State, single-core dynamic, and gas drive gave values in close agreement, but the Hassler method gave consistently lower values. G. D. H.

2047. New reserves tool. H. D. Ralph. *Oil Gas J.*, 3.5.51, **49** (52), 53.—Results of a study of the use of carbon dioxide in water-flooding operations indicate that oil recovery may be greatly increased by this method. A 25% solution of CO_2 in brine is reported under certain conditions to remove over 75% of the recoverable oil. Tests have been carried out on thirty-five cores from the Mid-Continent, and field tests are being made in the Penn Grade area, New York, and in northeastern Oklahoma, in which both fields have been water-flooded to the economic limit.

Limiting factors in the use of CO_2 for recovery appear to be the concentration of CO_2, temperature and pressure of flood water, crude gravity, and natural-gas content of the crude. C. A. F.

2048. Field experiments with chemical tracers in flood waters. P. W. Sturm and W. E. Johnson. *Producers' Monthly*, Dec. 1950, **15** (2), 11.—The general nature of a reservoir may be estimated from the study of tracer movement in the sand body. Tests conducted by the Bradford laboratory of the Pa. Grade Crude Oil Assoc. have shown the relative advantages of salts, fluorescent dyes, and surface-active agents.

Fluorescein was found to have good tracer qualities, in that it may be detected by the naked eye in concentrations of 1 p.p.m., and under the ultra-violet lamp in concentrations of 1 part in 50 million. Fluorescein does tend to be adsorbed, but not to an extent such as to restrict its use as a tracer. Provision was made for the injection of the tracer without discontinuing the flow. Operations on three leases are considered in detail.

The application of brine tracers, essentially the tracing of the chloride ions, was found to have application in waters of relatively low brine content. Thus waters with natural chloride contents of 1900 to 2400 p.p.m. were unsuitable owing to the difficulty of noting any increase. Brine has the advantage of not being adsorbed in the reservoir.

Surface-active agents have been used on a small scale. Radioactive tracers showed some possibilities, but few isotopes were found suitable to the method; these were either expensive or dangerous.

The experiments have indicated that occurrence of crevices, etc., is wider than originally assumed. A. J. H.

2049. Review of studies on factors affecting recovery by a water flood. R. F. Nielsen. *Producers' Monthly*, Dec. 1950, **15** (2), 19.—A review of some experiments conducted on long cores, in which the effects of the possible variables are considered. The conclusions are summarized. Sixteen references. A. J. H.

2050. The variation in water flood performance with variation in permeability profile. J. P. Schmatz and H. S. Rahme. *Producers' Monthly*, July 1950, **14** (9), 9.—The complexity of the permeability profiles of sand bodies has hitherto necessitated the general assumption of a uniform average sand permeability. An attempt is made to correlate certain ideal permeability profiles with production data

from hypothetical sands. All variables, other than permeability, were maintained constant.

Calculations are based on the independent methods of Stiles and Suders, and were carried out for six possible permeability distributions: homogeneous, circular, parabolic, probability, straight line, and factual data. The differences in results are due to the individual approaches: Stiles assumes a constant injection rate and variable pressure in a linear flow system; Suder assumes a constant injection pressure and variable flow rate in a radial system.

Reference is made also to the "Lorenz coefficient of heterogeneity," which is determined from a plot of the cumulative capacity versus the cumulative thickness. The use of this coefficient and the limitations of the described method are considered.

References. A. J. H.

2051. Selective plugging in the Bradford Field. H. H. Danielsen and D. Martin. *Producers' Monthly*, Nov. 1950, **15** (1), 15.—Production from the Bradford Field has been much complicated by the stratified nature of the producing sands. In the event of secondary recovery by water flooding, the amount of wasted energy is appreciable unless remedial action is taken. The application of selective plugging reduces, therefore, the overall consumption of energy and the use of water, while increasing the production of oil.

An improved method of plugging is described, in which greater use is made of the transient back pressure, by injecting the plugging agent directly into the tubing, against the existing pressure. Use is made of pressure fall-off curves as a measure of the effectiveness of the operation. Field results are considered in the light of improved recovery, and are given in tabular and graphical forms.

References. A. J. H.

Oilfield Development

2052. Developments in Arkansas and North Louisiana in 1950. L. D. Collier. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1345–51.—The area considered includes all of Arkansas and that part of Louisiana north of and including the following parishes: Sabine, Natchitoches, Grant, LaSalle, Catahoula, and Concordia.

Drilling activity in Arkansas and North Louisiana in 1950 decreased 3% under the 1949 rate. There were 306 exploratory wells and 1439 field-wells drilled in the year.

Oil production in 1950 was 82,829,610 brl, representing a 2% increase over 1949.

Discoveries in Arkansas consisted of eight new oilfields, four extensions, and three new producing zones. In North Louisiana, there were twelve new oilfields and three new distillate fields discovered; thirteen extensions and seventeen new producing zones were added to proved fields of North Louisiana. E. N. T.

2053. Developments in Arizona, western New Mexico, and northern New Mexico in 1950. P. H. Umbach and F. C. Barnes. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1266–73.—Exploration drilling in this area was concentrated in northern and western New Mexico, where thirty-two wildcats were drilled for a total footage of 120,152 ft. This represents an increase of twenty-one wells and 282% in total footage drilled over 1949 for this classification.

Some 109 wells were drilled in 1950 in western and northern New Mexico, compared with forty-three wells in 1949.

Geophysical work during 1950 was centred in the San Juan basin of New Mexico, with 201 crew weeks of seismograph, seventy-nine crew weeks of gravity, and seventeen crew weeks of magnetic work.

Production of oil in 1950 totalled 333,697 brl, with 14,391,350 M.c.f. of gas.

E. N. T.

2054. Developments in Atlantic coastal states between New Jersey and South Carolina in 1950. H. G. Richards. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1366–8.—Activity on the U.S. Atlantic coastal plain during 1950 was limited to two wells drilled in North Carolina and two in South Carolina; all were dry. Three wells were drilled in Garrett County, Maryland; one produced gas, and two were dry. Activity increased in western Virginia with twenty-seven new wells completed, thirteen producing gas, two oil, the remainder being dry holes. E. N. T.

2055. Progress report : Illinois water floods. Anon. *Oil Gas J.*, 1.3.51, **49** (43), 42.—Thirty-one controlled water floods were operating in Illinois at the beginning of 1950. Cumulative flood production to Jan. 1950, including the McClosky dump floods, was 15,400,000 brl.

Water-flood history and development are described for the following fields : Siggins, Bellair, Main, South Maunie, Bridgeport, and Patoka, and a table gives field data for thirty-one controlled water-flood fields as at Jan. 1950. C. A. F.

2056. Developments in Illinois and Indiana in 1950. A. H. Bell and R. C. Cooper. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1206–18.—In Illinois and Indiana, 4424 wells for oil and gas were drilled in 1950, as compared with 4018 in 1949, an increase of 10%. Total oil production decreased 3%, from 74,139,000 brl in 1949 to 71,914,000 brl in 1950. Wildcat drilling increased from 1217 completions in 1949 to 1334 completions in 1950, an increase of 10%. A total of fifty-five new pools, 102 extensions, and sixty-four new producing zones was discovered in the two states in 1950.

In the Illinois basin area—southern Illinois and southwestern Indiana—fifty-one out of fifty-eight discovery wells of new pools discovered in 1950 produced from Mississippian formations (twenty-seven in Chester series and twenty-four in Lower Mississippian). Of the remaining seven discovery wells of new pools, three produced from Pennsylvanian sandstone and four from Devonian limestone. E. N. T.

2057. Oil and gas developments in Kentucky in 1950. E. Boyne Wood. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1195–201.—Oil and gas production occurs in three general sections of Kentucky : the eastern, south-central, and western. Most of the oil comes from the western section, and the eastern part produces a very large percentage of Kentucky's natural gas. There are three tables in this paper showing : completion summary ; production ; important discoveries.

An increase in drilling activity occurred in Kentucky in 1950, resulting in a substantial gain in oil production. Western Kentucky accounted for both of these increases. Most of the gas development took place in the Big Sandy gas field of eastern Kentucky, though some increase in production was made in Knox County. There was little activity elsewhere in the state, and drilling to the St Peter and Knox horizons dropped sharply.

Actual production of oil in Kentucky was 10,096,073 brl, together with 150,000 M.c.f. of gas. E. N. T.

2058. Developments in Louisiana Gulf Coast in 1950. E. A. Murchison, Jr., and J. L. Patton. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1338–44.—The Louisiana Gulf Coast comprises thirty-eight parishes in South Louisiana. It is bounded on the north by Sabine, Natchitoches, Grant, LaSalle, Catahoula, and Concordia parishes ; on the west by the state of Texas ; and on the east by the state of Mississippi.

This paper consists mainly of a series of tables showing : summary of operations ; fields discovered ; important (outposts) extensions ; important new pools (new sands).

The statistical data on exploratory drilling show the discoveries for 1950 were completed as follows : one Pliocene completion ; seven Miocene completions ; six Oligocene completions ; three Eocene completions.

Preliminary data for the total production of oil and condensate in 1950 give a total of 166,856,472 brl, with 3,000,000 M.M.c.f. of gas. E. N. T.

2059. Field activity healthy, with deep holes commonplace. Anon. *Oil Gas J.*, 21.6.51, **50** (7), 173.—During the past year South Louisiana oil production reached 500,000 b.d., with gas production approx 2,000,000 M.c.f/day.

In the Cox Bay area of Plaquemines Parish there are now twenty-two wells producing from eleven pays ; oil has been found offshore from Livingston Parish in Lake Maurepas.

A well in the Week's Island field was completed for 538 b.d. from 15,122 to 15,137 ft.

Fields discovered during the past year include : Glenmora, gas northeast of Morgan City, two gas-condensate fields near Opelousas and in Atchafalaya Bay. A number of important extensions to known fields were found. C. A. F.

2060. Developments in Mexico in 1950. E. J. Guzman and F. Mina. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1404–22.—The producing territory of Mexico is divided both geologically and geographically into three provinces or zones: northeastern Mexico, Tampico Embayment, and the Isthmus region.

Some 223 wells were drilled in Mexico during 1950, representing an increase of 37·6% over 1949. A total of 100, or 44·8% of the total number of wells drilled, were exploratory tests; of these, forty-three were completed as producers.

Discoveries made during 1950 included five new oilfields, twenty-one new oil or gas pools, and seventeen extensions. These discoveries were made through various methods, including reflection-seismograph work, surface and subsurface geology, gravity meter, and electrical-resistivity surveys.

Of the exploratory tests the most important geologically was the new-field wildcat Tuzandepetl No. 5, that drilled 8495 ft into the salt in an attempt to find production in formations below the thick salt bed. The well was abandoned in salt at the total depth of 9843 ft. Gas shows were found between 4640 and 9790 ft. A sandy shale 59 ft thick was found at the depth of 7447 ft, containing microfauna of the Oligocene (Deposito formation). The age of the salt bed is considered as Jurassic; therefore, this new palæontological evidence has been tentatively interpreted as due to overhanging conditions of the salt dome.

Total oil production in Mexico was 72,426,154 in 1950, with 62,221,388 M.c.f. of gas.
E. N. T.

2061. Developments in North Mid-Continent in 1950. A. N. Sharrick. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1227–34.—The area covered in this report includes Kansas, Missouri, Iowa, and Nebraska east of the 100th meridian. Activity in all of these states except Kansas was relatively subordinate, although Nebraska showed a marked increase in activity over the previous few years. The area covered in detail does not include the shallow developments in southeastern Kansas, but is essentially the same as covered by reports of previous years.

Development and exploration drilling in Kansas reached its greatest volume since 1918. More than 4000 wells were drilled. Of this number, exploration accounted for 974 wells, discovering 104 oil pools, four gas pools, and eighty-one classified as either extensions or new producing zones in old pools.

Kansas produced 111,034,737 brl of oil and casinghead gasoline, and 324,261,344 M.c.f. of gas during 1950.

There were no successful wildcats in either Missouri or Iowa. In Nebraska east of the 100th meridian, there were three extensions to the Barada pool and one new-field discovery in Harlan County.
E. N. T.

2062. Developments in Michigan in 1950. W. A. Sanger. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1219–26.—This paper has tables showing: completion summary; production; distribution of wildcat completions by districts; new-field discoveries; new-pool discoveries; successful outposts.

In Michigan in 1950 there was a total of 336 oil-well completions, which includes twenty-six successful exploratory wells, a decline of 22·58% under the 1949 totals and accounts for 37·88% of the total well completions. Gas-well completions continued to decline with a total of seventy-six for the year as compared with ninety-two for the year 1949. Gas-well completions accounted for 8·6% of total completions.

Wildcat areas, mainly the western and northern districts, have received greater attention than in the preceding year, and will probably hold this attention for the ensuing year. With the increase in geological testing expected in 1951, exploratory drilling should also start on the up-grade for the coming year, unless too much area is condemned for further exploration.

Oil production in Michigan in 1950 was 15,826,148 brl, and gas production 12,614,024 M.c.f.
E. N. T.

2063. Field activity generally low; Mississippi eyes depth record. Anon. *Oil Gas J.*, 21.6.51, **50** (7), 174.—The South Carlton field in Alabama, which was discovered in 1950, now has six producers in the Massive from pays at 5300 and 5400 ft.

In the last eleven months fifteen producers have been completed in the Gilbertown field, where there are now sixty-four wells. Weekly production from the two fields in Alabama has reached 2750 b.d.

In Florida the Sunniland field is producing from twelve wells, of which eleven are pumping. Daily average production is 1650 brl.

Seven wildcats have been drilled in Georgia since June 1950; all were dry.

In Mississippi gas has been found in 1 Tung Oil Corp., near Wiggins, Stone County, from approx 20,290 ft. Production of the state has reached approx 100,000 b.d.

C. A. F.

2064. Developments in New York in 1950. E. R. McAuslan. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1173–6.—In the state of New York in 1950, five Oriskany sand wells were completed, as compared with thirteen completions in 1949. None of the wells was successful, and all reported salt water in the Oriskany sandstone. The total drilled footage for new Oriskany tests was only 23,369 ft, a new record low for the state.

In the Medina gas-sand area of the state, which includes Cattaraugus, Chautauqua, and Erie counties, there were about forty wells drilled, an increase of three over 1949. Of these forty, at least twenty-two were in storage fields in Erie County and ten were dry holes in existing pools in Erie County.

There were at least five shallow tests drilled, as compared with six in 1949. None of these tests was successful. These five wells aggregated only 6657 ft of footage.

Total oil pipeline runs during 1950 totalled 4,096,840 brl, with a daily average of 11,224 brl. This is unfavourable, comparable with the 4,216,000 brl produced in 1949. The record high production in New York was 6,685,000 brl in 1882.

There was no geophysical work with reference to oil or gas during the year, and the geological work was minor and confined to small areas by local companies.

E. N. T.

2065. Developments in Ohio in 1950. R. L. Alkire. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1188–91.—A rapid decline in gas discoveries, in nearly every producing county in Ohio during the early months of 1950, resulted in a sharp drop-off in gas drilling and increased activity in the oil-producing areas. Steady increases in crude prices further stimulated the search for oil. Some 1140 wells were reported completed in forty-nine counties during the year. Discoveries amounted to 144,833,000 cu. ft. of gas and 10,328 brl of oil initial per day. These were derived from 284 gas wells drilled in thirty-three counties, 282 oil wells in twenty-four counties, and 100 combination wells in seventeen counties. A total of 42%, or 476 of all wells drilled, resulted in dry holes. Total footage drilled amounted to 2,249,195 ft. Of this, 628,237 ft discovered gas, 512,261 ft found oil, 183,386 ft produced both oil and gas, and 924,014 ft proved unsuccessful. The average depth of all wells drilled was 1969 ft.

There were no geologically important test wells completed during the year.

E. N. T.

2066. Developments in Oklahoma in 1950. R. Engleman. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1235–46.—The following tables are presented to show Oklahoma's progress in 1950: completion summary; production; number, footage, and percentage success of exploratory wells; comparison of average initial potentials of oil and distillate discoveries from 1946 to 1950; successful new-field wildcats; successful new-pool wildcats; successful outposts; successful deeper-pool tests; successful shallower-pool tests; geophysical and core-drill crews reported at end of each month; important dry exploratory tests.

Increased wildcat drilling during 1950 resulted in an increase in discoveries, but not, probably, in reserves established per discovery. Overall reserves increased considerably, due to the one major discovery, North Milroy in Stephens County, and increased development drilling with numerous revisions and extensions of older fields. Secondary recovery commenced in earnest, jumping total projects from three in 1949 to fifty by the end of 1950, and reserves will begin to show an increase from this source in 1951.

Production of oil in Oklahoma totalled 163,031,347 brl in 1950, together with 607,918,141 M.c.f. of gas.

E. N. T.

2067. Developments in Pennsylvania in 1950. C. R. Fettke. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1177–87.—This paper contains seven tables: completion

summary, Pennsylvania, 1950; production in Pennsylvania, 1950; important discoveries; important dry exploratory tests; shallow-sand well completions; shallow-sand wells deepened; deep wells completed in western Pennsylvania 1950.

Exploratory drilling in the shallow-sand territory of western Pennsylvania (Upper Devonian or higher) during 1950 led to the discovery of only one small new gas field. No new oil pool was discovered. The total number of shallow wells drilled was 14·5% less than in 1949. The average daily oil production in the state in 1950 was 32,395 brl, as compared with 31,347 brl in 1949, an increase of 3%.

A total of thirty-four new wells was completed to the deeper formations (Onondaga or deeper) as compared with twenty-seven in 1949. Of these, two were drilled for gas-storage purposes. Of the remainder, nineteen were gas wells and thirteen were dry holes.

The outstanding event of 1950 was the discovery of another major Oriskany sand gas pool in north-central Pennsylvania early in the year. A wildcat well on the Leidy dome in Clinton Country in north-central Pennsylvania encounted an open-flow of gas estimated at 15 million cu. ft/day in the top of the Oriskany sandstone.

E. N. T.

2068. Natural gas developments in North-Central Pennsylvania. J. W. Hendrickson. *Producers' Monthly*, Oct. 1950, **14** (12), 13.—A brief report is given of the discovery of gas in the Oriskany sand in Leidy Township, Clinton County, Pa., on Jan. 8, 1950. The first well had an estimated original open flow of 17 million cu. ft. at a rock pressure of 4200 p.s.i. A. J. H.

2069. Developments in Rocky Mountain region in 1950. C. L. Severy and D. M. E. McCarty. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1160–72.—In this report the Rocky Mountain region includes Colorado, Utah, Montana, Wyoming, Idaho, North Dakota, South Dakota, and for the first time, that part of Nebraska west of the 100th meridian.

Rocky Mountain exploratory drilling reached its peak in 1950. Of 406 wells drilled, eighty-three were successful and thirty discovered new fields. Successes increased 4% over the previous year to the total of 20·4%. Again Cretaceous sands were the primary objectives, and nearly three-quarters of the new producers were in these formations. For the first time geophysical methods led in the discovery of new fields in the region.

Highlight of exploration in 1950 was the rapid and successful development of the eastern flank of the Denver–Cheyenne basin in northeastern Colorado and western Nebraska. Thirteen Cretaceous new-field discoveries were made in this basin. This year marked the entrance of western Nebraska as a full-scale oil-producing area. In the Powder River basin of Wyoming additional discoveries were made on the flanks of large known structures, as Cretaceous stratigraphic traps and fault accumulations carried on the exploratory trend of the previous year. In the Big Horn basin of Wyoming, deeper drilling was given impetus by the Permian discovery at Slick Creek.

E. N. T.

2070. Developments in southeastern states in 1950. F. T. Holden. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1352–65.—For the purposes of this paper the southeastern states are restricted to those active in exploration: Alabama, Florida, Georgia, and Mississippi.

In Alabama twenty-three wildcats resulted in two new-field discoveries. Some eighteen new producers were completed, and oil production amounted to 721,782 brl, bringing the cumulative total of 2,748,861 brls.

Florida wildcatting declined more than 50% to a total of nine tests for 1950. One new producer was drilled, and the year's production of 463,093 brl brought the total cumulative to 1,554,607 brl.

In Georgia three dry wildcats were drilled and two crew weeks were worked by a geophysical crew.

Mississippi wildcats totalled 133, resulting in nine new fields. There was little fluctuation in geophysical exploration in Mississippi during 1950. E. N. T.

2071. Oil and gas developments in Tennessee in 1950. H. C. Milhous. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1202–5.—While activity was high in Tennessee in the early and closing months of 1950, a mid-year lull in exploration resulted in an unusually

small number of completions and a low figure for footage drilled. There were thirty test wells completed with a total footage of 31,207 ft, making an average of a little more than 1000 ft per hole.

Oil production for the year was 11,781 brl, with more than 80% coming from Morgan and Scott counties in the northern part of the Cumberland Plateau. Production there is from middle and upper Mississippian limestone which range in depth from 700 to 1500 ft below the surface. The remaining production was from Pickett, Fentress, and Clay counties.

Total gas production was estimated as closely as possible at 88·5 million cu. ft. Morgan and Scott counties produced approx 88%, the balance coming from the Jamestown field in Fentress County. E. N. T.

2072. Development in Upper Gulf Coast District of Texas in 1950. H. H. Allen. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1322–37.—The Upper Gulf Coast District of Texas is composed of twenty-nine counties in the extreme southeastern part of the state. The area contains the largest concentration of refineries, gasoline plants, and petrochemical plants in the world.

Drilling showed a 24·5% increase over 1949, with 1626 tests being completed in 1950. These tests resulted in 1135 producers, a successful completion rate of 69·8% There were 216 new-field wildcat tests drilled in 1950, as compared with 179 tests in 1949.

There are five tables which show: completion summary; production; new-field discoveries; new sands, new reservoirs, and extensions discovered; geophysical activity by counties (crew weeks).

A total of 169,195,600 brl of oil and condensate were produced during 1950. E. N. T.

2073. Mustang Island has yielded 10 pay sands. W. P. Sterne, *Oil Gas J.*, 21.6.51, **50** (7), 194.—Forty-one wells have been completed in the Mustang Island field in Corpus Christi Bay, Nueces County, Texas, which was discovered in Sept. 1949. Ten pays have been found in the Oligocene Frio, of which the Sand 8 or the " 7200 ft " is the most developed. All wells are drilled from barges.

The average depth of wells is 8000 ft, and overall drilling time is approx thirty days. Reservoir pressures vary from 3000 to 3500 p.s.i., and gravity averages 40°. Wells are fitted with borehole storm chokes, and surface fittings are protected by caissons. C. A. F.

2074. Developments in Texas Panhandle in 1950. W. J. Vaughn, Jr. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1247–53.—The Panhandle district of Texas, as covered in this report, includes the twenty-six counties in the Texas Panhandle, which comprise Texas Railroad Commission District 10. It is bounded on the north and east by Oklahoma, on the west by New Mexico, and on the south by the south lines of Parmer, Castro, Swisher, Briscoe, Hall, and Childress counties. A total of eleven of these twenty-six counties produce oil or gas or both. With exception of the production from two small fields discovered in 1949, all of the gas and oil is produced from the interconnected reservoirs of the combined Panhandle and Hugoton fields. The major structural features which occur within the district are: the Anadarko basin in the northeastern part, the Dalhart basin in the northwestern part, the Palo Duro basin or Plainview basin in the southern half, and the buried Amarillo Mountains which underlie the major part of the Panhandle oil and gas field and separate the Palo Duro and Anadarko basins.

Drilling activities in the Texas Panhandle continued to increase in 1950 over preceding years. In all, 825 development and thirty exploratory wells were drilled during the year. No new fields were discovered; however, five exploratory tests were completed as field extensions and one as a shallower-pool discovery. Oil production remained constant, with more than 33 million brl produced, while gas production decreased by 112·6 (U.S.) billion cu. ft., with a total of 862 (U.S.) billion cu. ft. produced for the year. E. N. T.

2075. Developments in East Texas in 1950. M. Hays, Jr. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1313–21.—The East Texas district as covered in this report includes forty-six counties in the northeastern corner of the state. Comparative references to

former years have been adjusted to conform with these boundaries. Texas Railroad Commission Districts 5 and 6 are composed of these forty-six counties, and the additional counties of Grayson, Johnson, and Bosque, on the west edge of District 5, are not normally included in the East Texas geological district.

A total of twenty-two new-field and new-pool discoveries were drilled; fourteen of the twenty-two were considered new-field discoveries; four were shallow-pool discoveries; four were deeper-pool discoveries; and the remainder of the 169 exploratory tests were dry holes. Fifteen new oil and seven new gas reservoirs were found. These developments include new production from formations as follows: Woodbine 8, sub-Clarksville 3, Buda 3, Rodessa 2, and one each from the Paluxy, Pettit, Hill, upper Glen Rose, Goodland, and Nacatoch. Although some of the fields appear to be of moderate size, none can be considered a major discovery. New producing zones were discovered in the Tennessee Colony, Red Lake, Ham-Gossett, Walter Fair, Carthage, Yantis, and Pine Mills fields.

The district's total production for 1950 was 143,534,100 brl, as compared with 141,241,000 brl in 1949. E. N. T.

2076. Developments in North Texas in 1950. H. H. Bradfield. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1274–93.—The North Texas District covered in this report includes sixteen counties in the north-central part of the state south of the Red River or Texas–Oklahoma boundary. All of the counties except Collin County produce oil. The major structural features of the North Texas area covered in this paper are as follows: Red River (Electra) arch; Muenster arch; Bend flexure; Fort Worth basin; Marietta–Sherman basin; Hardeman basin; Knox–Baylor (Benjamin) basin.

Production has been gradually increasing over the past several years, and last year totalled 54,517,151 brl. The total number of wells drilled, 3415, was the greatest of any previous year. Of this number, 1940 were productive in oil, fifteen gas, and 1460 dry. Of the 673 exploratory holes drilled, 139 were discoveries and 534 dry. The total exploratory footage was 2,429,951. Archer, Clay, Jack, and Montague counties lead in the order named. The most important discoveries were the Sandusky Ordovician production in Grayson County and Canyon reef production in Knox County. E. N. T.

2077. Wildcatting up after 1950 decline. Anon. *Oil Gas J.*, 21.6.51, **50** (7), 168.—Approx 118 new fields have been discovered in southwest Texas during the last year, and additional new pays to existing fields have been found. The new fields include: Helen Gohlke in DeWitt County, which now has sixteen oil and two condensate producers in the Wilcox; a Wilcox pay 25 miles to the southeast of this field, where four producers have been completed; the Portilla Frio field discovered in Feb. 1950; and the Swan Lake field off Lavaca Bay in Jackson County, which has eight oil and three gas pays also in the Frio. C. A. F.

2078. Developments in South Texas in 1950. B. Scrafford and N. Jenswold. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1300–12.—Because of the size of the South Texas district, the authors have subdivided the area into stratigraphic sections based on the geologic age of productive and potentially productive trends. These subdivisions are as follows: the pre-Cretaceous; the Cretaceous; the Queen City, Reklaw, and Carrizo–Wilcox of the lower Eocene; the Jackson and Yegua of the upper Eocene; the Frio and Vicksburg of the lower Oligocene; and the Catahoula and Oakville of the upper Oligocene and lower Miocene.

An increase of 15% in the rate of development was noted in comparison with the drilling activity in the South Texas area during the previous year. In all, 3036 wells of all categories were drilled, 2293 in proved areas, and 743 were classified as wildcat tests.

There is a table giving the South Texas fields discovered in 1950.

The total oil production from the South Texas district amounted to 129,792,724 brl, and an additional 19,182,512 brl of hydrocarbon liquids were processed from the gas production. E. N. T.

2079. Developments in West Texas and Southeast New Mexico in 1950. H. A. Miller, Jr., *et al.* *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1254–65.—The number of explora-

tory tests drilled in West Texas and Southeast New Mexico in 1950 exceeded that of the previous year by 69·7%, and successful new-field wildcats increased by 32%; development drilling increased by 42%. There were one and one-third times as many pre-Permian discoveries as Permian. Discoveries by seismograph were double those found by subsurface means.

The outstanding developments of the year were reef-limestone exploration, intense Spraberry development in the Midland basin, pre-Permian structural development in the Midland basin, and increased pre-Permian drilling on the northwest shelf area of New Mexico.

It is anticipated that exploratory drilling in the Midland and Delaware basins and the northwest shelf area of New Mexico will continue to increase during 1951.

The total oil produced in the area under review during 1950 was 340,163,800 brl.

E. N. T.

2080. Developments in West-central Texas in 1950. R. H. Martin. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1294–9.—West-central Texas includes the twenty-four counties near the geographical centre of the state, which comprise Texas Railroad Commission District 7-B. The extreme south part of this area is on the Llano uplift, the eastern part is in the Fort Worth basin, and the western part is on the Eastern platform of the Permian basin. The Fort Worth basin and the Eastern platform are separated by the Bend arch, a north–south-trending, broad flexure passing through Brown, Eastland, and Stephens counties.

This area is one of relatively shallow production, with depths ranging from 150 ft in Brown and Callahan counties to slightly below 7000 ft in Nolan County. Production is from the Wolfcamp formations of the Lower Permian, the Cisco, Canyon, Strawn, and Bend sediments of the Pennsylvanian, the Chappel reef limestones of the Mississippian, and the Ellenburger dolomite of the Lower Ordovician. Pennsylvanian reef limestones are well developed in the west half of this area and either produce or account for the production in many wells.

There are tables which show: completion summary; production; new-field discoveries; statistics on exploratory methods.

Total oil production in this area was 25,752,000 brl, together with 59,153,000 M.c.f. of gas.

E. N. T.

2081. Progress report: Uinta Basin development activity. E. A. Polumbus. *Oil Gas J.*, 7.6.51, **50** (5), 78.—Cumulative production from the Tertiary sediments of the Uinta Basin has reached 400,000 brl since oil was first discovered in commercial quantities in these rocks in 1949.

There are numerous oil shows at surface in the basin; these include the oil sands of Asphalt Ridge, and veins of gilsonite, wurtzilite, and ozokerite. The four main Tertiary formations in the basin are the non-marine Duchesne River, Uinta, Green River, and Wasatch. In 1949 a wildcat near Roosevelt flowed 1633 b.d. of 33° oil from the fractured Green River shale from 9351 to 9392 ft. A second well 7 miles to the southeast in this area also found oil in the Green River. A subsequent well discovered the Red Wash field 35 miles southeast of the Roosevelt discovery, and on test flowed 275 b.d. from approx 5200 ft.

Drilling practice in the area is outlined. There appears to be a general relationship between depth and penetration rate, penetration declining approx 20% per 100 ft.

C. A. F.

2082. Oil and gas developments in West Virginia in 1950. R. C. Tucker. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1192–4.—A table is presented which gives oil and gas operations in West Virginia by counties in 1950. This table also shows comparisons with 1947, 1948, and 1949. Ten less gas wells, twenty-eight more oil wells, ten more oil and gas wells, three more storage, brine, water-intake, and pressure wells, and thirteen more dry holes were completed in 1950 than in 1949. Permits to drill or deepen issued by the State Department of Mines totalled 848, or thirty-five more than were issued in 1949. Total completions were 744, as against 700 in 1949. Jackson County, with eighty-one completions, topped the list of completions by counties, followed by Pleasants with seventy-five, Ritchie with fifty-two, Wood with forty-nine,

Calhoun with forty-seven, Wayne with forty-three, and Lincoln and Putnam with thirty-four each. These eight counties accounted for 56% of the completions.

Total oil production in the state was 2,788,000 brl in 1950; total gas production was 197,210,000 M.c.f. E. N. T.

2083. Developments in West Coast area in 1950. G. B. Moody. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1142–59.—The area covered by this report includes Washington, Oregon, Nevada, and California.

Two of the three 1950 new-field wildcats in Washington were interesting tests. The Union Oil Co.'s State No. 3 reached a total depth of 9359 ft. It was tested through perforations at intervals between 3670 and 6400 ft. A small amount of high-gravity oil was produced from the intervals 3670 to 4440 ft and 4663 to 4676 ft. This non-commercial oil came from the Nye formation (Miocene).

Exploratory results in Oregon were not encouraging. The four unsuccessful efforts that made a total of 12,954 ft of hole were not, however, particularly significant as tests of the oil and gas possibilities of the state, except that they disproved the presence of oil and gas at the particular locations chosen and to the depths drilled.

The two new-field wildcats abandoned in Nevada in 1950 drilled 10,814 ft, but one of them accounted for 10,314 ft of hole. This well was located on a surface structure, and was a good, although disappointing, test of the oil and gas possibilities of that structure. Showings of oil and gas were encountered, but they were not sufficiently promising to warrant drilling a second well. The formation exposed at the surface location was the Chairman shale of Upper Mississippian age, and the bottom of the hole was in a dolomite formation of Silurian age.

Total exploratory footage in 489 exploratory wells completed as producers or abandoned as dry holes in California in 1950 was 1,911,924 ft. Comparable figures for 1949 were 588 wells and 2,138,501 ft. Exploratory activity during 1950 decreased 16·8% as to number of wells and 10·6% as to footage from the record levels of 1949. Exploratory wells were 14·4% and 16·8% successful as to number and footage, respectively. The successful wells discovered thirty new pools and fields, but none has given indication of being a major discovery. Production during the year was about 327,607,000 brl of crude oil, 28,217,000 brl of natural-gas liquids, and 532,396,000 M.c.f. of gas (includes gas from dry-gas fields and residue gas from oilfields). Basement was reached by sixty-five unsuccessful wells. There were sixty-seven exploratory wells active at the end of 1950. E. N. T.

2084. Developments in Alaska in 1950. R. L. Miller. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1369–79.—In 1950 intensive exploration took place on the Arctic Slope of Alaska in and near Naval Petroleum Reserve No. 4, where the U.S. Navy has been conducting investigations since 1944. The geophysical parties worked entirely within the reserve, doing both regional reconnaissance and detail shooting for drilling site. In addition, eleven wells were drilled or drilling in 1950. Several of these were deep tests, including one that bottomed at 11,872 ft. All but one of the wells were entirely within the Lower Cretaceous part of the section after the mantle of Pleistocene gravel was penetrated. As the result of the 1950 drilling, the Navy has announced the discovery of "two minor oilfields." E. N. T.

2085. Developments in Eastern Canada in 1950. W. A. Roliff. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1380–7.—This paper outlines the exploratory and development activities in 1950 in the sedimentary basins in the provinces of Ontario, Quebec, New Brunswick, Nova Scotia, Prince Edward Island, and Newfoundland in Eastern Canada. During the year 1950, development drilling was carried out in the south-western Ontario and Maritime basins, and exploratory drilling in these and in the Hudson's Bay Lowlands and Gaspe.

Exploration activity in Eastern Canada declined somewhat during 1950; a total of sixty-two wells were drilled, compared with eighty-five wells in 1949. Two small new gas pools and two small deeper gas pools were discovered in southwestern Ontario. During the year gravity surveys were carried out in southwestern Ontario.

Development drilling was on approx the same scale as in 1949, 280 development wells being completed, 277 in Ontario and three in New Brunswick. Oil production in 1950 amounted to 265,883 brl, and gas production to 11,093,570 M.c.f. E. N. T.

2086. Developments in Western Canada in 1950. J. O. Galloway. *Bull. Amer. Ass. Petrol. Geol.*, 1951, **35**, 1388–403.—This paper deals with petroleum and natural-gas developments in Western Canada, and in particular in the provinces of Alberta, Saskatchewan, Manitoba, and British Columbia, since development in the Northwest Territories was at a standstill in 1950.

The total number of wells drilled in Western Canada in 1950 was 1116, of which 1034 were drilled in Alberta, sixty-four in Saskatchewan, six in Manitoba, and twelve in British Columbia. Alberta had 796 development wells and 238 exploratory wells. Of the 238 exploratory wells, thirty-one were outpost, fourteen were new-pool, three were deeper-pool, and 190 were new-field. There were discoveries of forty-four oil wells, eighteen gas wells, and one gas-condensate well. Dry holes numbered 175 wells. The discovery rate in Alberta was 26·5% of all exploratory wells drilled. Drilling rigs were scarce in the latter part of the year, with 140 rigs in operation.

It is interesting to note, however, that of the thirty-eight discoveries made in Alberta during 1950, only eight were made by major companies. Two were financed mainly by major company funds, but were drilled by the small operator. The rest of the discoveries, twenty-eight, were made by the minor or independent operators.

Daily oil production in Western Canada averaged 74,000 b.d. during 1950.

E. N. T.

2087. Alberta report. Anon. *Oil Gas J.*, 8.3.51, **49** (44), 58.—27,595,664 brl crude and natural gasoline were produced in Alberta in 1950, or 75,605 b.d., compared with 55,470 b.d. in 1949. Cumulative production to the end of 1950 was 155,950,387 brl.

Gas production in 1950 was 82·2 (U.S.) billion cu. ft., compared with 58·97 (U.S.) billion cu. ft. in 1949. C. A. F.

2088. German reserves climb. Anon. *Oil Gas J.*, 10.5.51, **50** (1), 88.—Estimated crude-oil reserves of Western Germany are 38,025,000 tons, or approx 270 million brl. 72% of this is classed as proved, and the remainder as probable. Proved reserves of Emsland are 18,900,000 tons. C. A. F.

2089. Modern drilling and production practice in the oilfields of South Iran. H. W. Lane. *Proc. Fourth Empire Min. Metall. Congr.*, 1950, **1**, 487–519.—After describing standard drilling practice in Iran, greater detail is given of some difficult operations peculiar to the fields. Emphasis is laid on pressure drilling technique, and the method of drilling through the gas dome is described. Safety practices are referred to.

Unit control and the production system for the limestone reservoirs are described. The surface-production system is dealt with in all its stages and the recycling system mentioned. G. S.

2090. Oil, are we running out of it? G. Egloff. *Midwest Engineer*, May 1951, **3** (9) 6.—A survey is given of the growth of the oil industry. World crude oil production and consumption are shown. The U.S. investment capital is discussed, and the energy uses in the U.S. are given for cars, trucks, buses, tractors, locomotives, and space heating. The search for oil and gas is discussed. Estimated and proved world and U.S. crude oil and gas reserves, and U.S. new reserves yearly increments, are recorded. Ultimate reserves are recorded and discussed. Tabulations of ultimate world oil reserves under land areas are given and oil under the Continental shelves discussed. It is considered that even the highest estimates of reserves are too low. W. H. C.

2091. New production record. D. M. Duff. *Oil Gas J.*, 21.6.51, **50** (7), 161.—Total world production in Apr. 1951 averaged 11,712,000 b.d., or 1·3% more than in the previous month. U.S.A. production was 6,144,000 b.d.

A table shows world crude-oil production for Mar. 1951, and Apr. 1950 and 1951, by countries. C. A. F.

2092. Production rising. Anon. *Oil Gas J.*, 7.6.51, **50** (5), 66.—Japan's crude output has been increased by 85% since 1948. 2,066,000 brl were produced in 1950, or an average of 5660 b.d. A further rise in production is predicted with the continued development of the deep zones in the Yabase field.

Japan's proved reserves at the beginning of 1951 were 26,306,000 brl, compared with 21,067,000 brl in 1950. C. A. F.

2093. Exploratory drilling in 1950. F. H. Lahee. *Bull. Amer. Ass. Petrol. Geol.*, 1951, 35, 1123–41.—This is the sixth annual report on data gathered and compiled by the A.A.P.G. committee on statistics of exploratory drilling. It is the fourteenth article of its kind, written by the same author and printed each year in the June issue of the Association's *Bulletin*.

There are fourteen tables showing: classification of exploratory wells; number of oil wells, condensate wells, and dry holes drilled in the U.S.A. as exploratory tests in 1950; basis for locating new-field wildcats drilled in 1950; basis for locating new-field wildcats; footage drilled in new-field wildcats; number of exploratory holes drilled in the U.S.A. in 1950, by classes and states; percentage of exploratory holes drilled in each class in the U.S.A. in 1948, 1949, and 1950; statistics on exploratory holes and footage drilled, and on average depth of exploratory hole in the U.S.A.; relative success of exploratory drilling in the U.S.A. from 1944 to 1950, inclusive; new-pool discoveries and extensions of older pools in the U.S.A. in 1950; fields discovered in 1944, 1947, and 1950, grouped according to their total ultimate reserves as estimated Jan. 1, 1950; exploratory drilling in Canada in 1950; basis for location of new-field wildcats in Alberta; exploratory drilling in Mexico in 1950.

These tables show that during 1950, 10,306 exploratory holes were drilled in the U.S.A. Of these 5290 were new-field wildcats, 2495 were new-pool tests (including new-pool wildcats, deeper-pool tests, and shallower-pool tests), and 2521 were outposts. Among the new-field wildcats, 592 were successful; among the new-pool tests, 642 were successful; and among the outposts, 780 were successful.

The total exploratory footage drilled in the U.S.A. in 1950 was 40,175,173 ft in the 10,306 holes, or 3898 ft per hole. These figures compare with 34,798,291 ft drilled in 9058 exploratory holes, with an average depth of 3842 ft, in 1949. E. N. T.

Transport and Storage

2094. Right or wrong? Post-war technical developments in shipbuilding, marine engineering and ship operation in the retrospective light of war-time planning. A. C. Hardy. *Svensk Sjöfarts Tidning*, Annual Issue, 1951, 30.—A review is given of shipbuilding planning during the last war for a problematic post-war world, by Britain, Canada, the U.S.A., France, Germany, Spain, Portugal, Denmark, and some of the South American states. Post-war developments are discussed from the following aspects: passenger-liner trends, owners and naval architects, cargo-handling problems, new cargoes and new methods, powering tendencies. W. H. C.

2095. Restraints on the expansion of vertical tanks under liquid head. P. Kerr. *J. Inst. Petrol.*, 1951, **37**, 209–23.—Formulæ are developed for the correction when necessary of tank tables for the restraining effect on expansion exerted by the tank bottom and roof, by buttstraps, and by horizontal and vertical seams. A. R. W. B.

2096. Cargo and ballast distribution in tank vessels. T. Andersson. *Svensk Sjöfarts Tidning*, Annual Issue, 1951, 36–46.—Stresses in a vessel during the normal life of a ship are discussed, and cargo and ballast distribution is described. Recommendations are given which are based on a routine investigation taking only statical forces into consideration. The ship, a 16,000-ton Borkum-built tanker, is considered as placed among waves 500 ft long (equal to the ship's length) and 25 ft in height (1/20th of length); first, with a wave crest and secondly, with a wave through amidships. Data are given of some 300 different cases of the ship in ballast and fully loaded conditions. When sailing in ballast the ship is assumed to have approx 30% of the whole bunker store and approx 60% of the water store. Recommendable ballast conditions and recommendable full-cargo conditions are discussed and shown in ship plans and tables. Voyages in ballast are discussed. Improper distribution of cargo when loading and order of filling, emptying, and cleaning are outlined. Voyages in fully loaded condition are described, and recommendations are given as to various gravity

products. Eleven tables and twenty drawings of tankers, showing the various ships' tanks, are given for dangerous ballast cases, dangerous fully loaded cases, suitable ballast, and suitable full-cargo conditions. W. H. C.

2097. Gas dehydration as an inhibiting factor in formation of hydrates in gas pipelines (according to I. E. Khodanovich, *Neft. Khoz.*, 1946, **5**). I. Niementowska. *Nafta*, Jan.–Feb. 1950, **6**, 38–9.—Removal of water from crude gases is necessary to avoid formation of loose compounds, *e.g.*, $C_3H_8.7H_2O$. Fugacity of water is greater than that of hydrates. Best dehydrating agents are solid, but they are difficult to apply. M. S.

2098. Leak location by radio-active gases in buried pipes. A. Germant, E. Hines, and E. L. Alexanderson. 1951, **22**, 460–4.—This paper describes basic considerations and experiments on leak location by means of radioactive tracer gases in underground pipes. C-14 labelled carbon monoxide and radon were used as tracers, the principles of the method being given. Techniques of preparing and detecting the tracer gases have been worked out, and calculation on the spreading of the tracer gas in a pipe are given. Leak location on two small-scale installations has been carried out. N. T.

Refinery Operations

Refineries and Auxiliary Refinery Plant

2099. Problems involved in building a refinery. D. D. Margules. *Brit. Petrol. Equip. News*, 1951, **2** (1), 22.—The problems involved in planning a refinery are discussed from the aspect of the relationship between the contracting engineers and the Council members, as it is felt that appreciation of the need of full co-operation does not always exist.

Plant " pay-out time "—the time required for oil processed in a plant, after deduction of operating and maintenance costs, to amortize the plant investment—is discussed from several aspects.

In planning a refinery a block flow diagram, showing the intake and required finished products, is given to the contracting engineers. A detailed study is necessary to process-design each particular unit. Whilst this is going forward it is necessary to plan construction activities. Overall refinery layout is reviewed, temporary roads planned, and site drainage for construction anticipated. Construction tools and heavy lifting gear are scheduled and purchased. Construction plans are affected by material delivery and availability of labour. While exact process requirements are being determined, plant layout (plot plans) is developed by a screening committee, covering instrumentation, piping, lines to tanks, etc. Basic equipment sizes are planned by the process department. Major equipment is described and planning time discussed. In this connexion, a fractionating-tower drawing, sent out for inquiry purposes, is discussed as an example. The various aspects of planning, receipt of equipment, and erection of units and auxiliaries are discussed with respect to preliminary and final plans for inquiries and final drawings for completion. Construction cannot go forward until engineering has reached a stage where drawings can actually be issued for construction purposes. The effect of delay in receipt of certified drawings from manufacturers, and the delay in delivery of equipment, are discussed.

Various points that would assure closer co-operation between the parties, noted above, are discussed, covering: shop loads, trade names, sub-suppliers, erection facilities, manufacturers' installation instructions, and service engineers. Two pages of the discussion following the paper are given. W. H. C.

2100. Thermal conductivity of granular beds filled with compressed gases. J. D. Weininger and W. G. Schneider. *Industr. Engng Chem.*, 1951, **43** (5), 1229–33.—Measurements of thermal conductivity of granular beds of aluminium oxide and borosilicate glass when filled with helium, hydrogen, nitrogen, or carbon dioxide at pressures up to 100 atm are reported. E. J. C.

2101. Nomograph of Dittus-Boelter equation for heating and cooling liquids. J. F. Heiss and J. Coull. *Industr. Engng Chem.*, 1951, **43** (5), 1226–9.—A nomograph is presented for calculating film coefficients for twenty-two non-viscous liquids over various temp ranges from −10° to 212° F. E. J. C.

2102. Portable heater using chlorinated biphenyl. R. E. Howard. *Industr. Engng Chem.*, 1951, **43** (3), 782–4.—A brief description is given in this report of a portable, electrically heated unit for heat-transfer duties, using chlorinated biphenyl and polyphenols as a non-inflammable, non-corrosive, liquid heat-transfer medium for temp up to 300° C. E. J. C.

2103. Refrigeration in the refining industry. Pt II. T. G. Hicks. *Refiner*, 1951, **30** (6), 145–6. (See Abs. No. 1835.)—The first article of this series discussed the elements of refrigerating systems used in refining and petrochemical operations. This part considers typical applications in various phases of modern refining and petrochemical processes, including dewaxing, alkylation, light-end recovery, reaction heat control, and air conditioning. R. W. G.

2104. Ion exchange in high temperature industrial applications. F. K. Lindsay, L. F. Wirth, and A. M. Durinski. *Industr. Engng Chem.*, 1951, **43** (5), 1062–5. A short paper dealing with the use of a polystyrene cation exchanger for water treatment after hot lime or lime soda treatment at 220° to 240° F. E. J. C.

2105. Carboyxlic cation exchange resin in water conditioning. F. X. McGarvey and J. Thompson. *Industr. Engng Chem.*, 1951, **43** (3), 741–6.—This report describes experiments carried out with a carboxylic cation-exchange resin primarily from the view-point of reducing hardness and alkalinity. From the plotted results, the authors deduced that whilst the flow rate and concentration sensitivity might impose severe limitations on the use of this type of exchanger, these deficiencies would be more than offset by the high capacity and high efficiency of exchange. E. J. C.

2106. C.P. glycerol by ion exchange. D. M. Stromquist and A. C. Reents. *Industr. Engng Chem.*, 1951, **43** (5), 1065–70.—Treatment of glycerol solutions prior to vacuum evaporation by ion-exchange methods is described. The method is reported to compare favourably with the steam-distillation process from an economic point of view, provided that the amount of ionized solids in the glycerol solutions before ion-exchange treatment is not greater than 10% for crudes or 2% for sweet waters. E. J. C.

2107. Gelation times of various silica sols. R. W. Spencer, A. B. Middleton, and R. C. Merrill. *Industr. Engng Chem.*, 1951, **43** (5), 1129–32.—This reports the study of gelation times of various silica-coagulant aids used in raw water and waste water treatment. Gelation times are given for mixtures at 25° and 8° C of dilute sulphuric acid or ammonium sulphate with a dilute 3·3 ratio sodium silicate containing 1 to 6% silica. E. J. C.

2108. Glycerol removal from aqueous solutions by anion exchange. S. E. Zager and T. C. Doody. *Industr. Engng Chem.*, 1951, **43** (5), 1070–3.—This paper reports experimental work carried out to remove glycerol by a continuous adsorption process. The method described relied upon strongly basic anion exchangers which were pre-treated with either boric acid or sodium tetraborate prior to use as an adsorbent.

No satisfactory method of recovery of the glycerol from the adsorbent is given.

Analytical methods used in this work resulted in the following equation :— $y = 0{\cdot}001247x + 1{\cdot}3221$, where x = weight % of glycerol in water, y = refractive index of glycerol at 20° C. E. J. C.

2109. Mixed-bed deionization. A. C. Reents and F. H. Kahler. *Industr. Engng Chem.*, 1951, **43** (3), 730–4.—A brief description of the theory of mixed-bed deionization is given, together with the method of operation and regeneration of industrial type equipment. The report includes some data on the analyses of water before and after treatment. E. J. C.

2110. Monobed deionization with ion exchange resins. R. Kunin and F. X. McGarvey. *Industr. Engng Chem.*, 1951, **43** (3), 734–40.—Details are given in this report of a laboratory apparatus for deionization of water using anion and cation resin exchangers intimately mixed in a column. By suitable choice of exchange resins it was found possible to obtain an effluent approaching the purity of conductivity water. Results are presented graphically. E. J. C.

2111. Silica removal with highly basic anion exchange resins. R. Osmun and L. Wirth. *Industr. Engng Chem.*, 1951, **43** (5), 1076–9.—The removal of silica from water for use in high-pressure boilers by means of pilot demineralizing plant is described in this article. Regeneration of the exchanger bed is described in detail. Studies of this latter operation revealed that the amount of caustic soda used and the time required were dependent upon the temp. E. J. C.

2112. Reducing water pollution for oil refineries. W. H. Redlien, Jr., and J. H. McClintock. *Refiner*, 1951, **30** (6), 123–6.—A discussion of the methods of overcoming water pollution problems experienced by affiliates of Standard Oil (New Jersey). R. W. G.

Distillation

2113. Selection and operation of distillation plant (1). A. Dummett. *Chem. Prod.*, July 1951, **14** (7), 257–60.—This article comprises the first part of a paper intended for the operator rather than the designer of distillation plant. The basic principles of fractionation are explained and applied to the selection of distillation plant. Consideration is given to the choice between batch and continuous distillation, the features of each being compared and contrasted. Finally, methods for controlling these processes are outlined. M. C. B.

2114. How to calculate distillations with variable relative volatility. M. Nord. *Chem. Engng*, 1951, **58** (2), 144–6.—The error of assuming constant volatility is appreciable in some systems. The general equation relating equilibrium vaporization constants is given, and from it applications to the ideal, non-ideal, and azeotropic systems are made, giving a straight-line relation between P_A and P_B the component vapour pressures. These cases are substituted into simple and multi-component batch distillation and to flash vaporization equations. A nomograph provided eliminates trial-and-error calculations. D. H.

2115. High temperature distillation. T. J. Walsh. *Industr. Engng Chem.*,1951, **43** (1), 63–8.—A review with 124 references. (Unit operations symposium 1951.) F. M.

2116. High vacuum distillation. K. C. D. Hickman. *Industr. Engng Chem.*, 1951, **43** (1), 68–9.—A review with fifty references. (Unit operations symposium 1951.) F. M.

2117. Pressure drop through bubble caps. Pt I. Introduction. J. L. Huitt and R. L. Huntington. *Refiner*, 1951, **30** (6), 131–4.—The first of a series of three articles considering pressure-drop calculations. The problem has been divided into the following sections, and equations relating pressure drop to the variables are presented: (*a*) flow reversal, (*b*) liquid seal, (*c*) slot opening, (*d*) surface tension, and (*e*) change in vapour velocity.

A list of thirty references to the literature is given. R. W. G.

2118. Azeotrope formation between sulphur compounds and hydrocarbons. D. H. Desty and F. A. Fidler. *Industr. Engng Chem.*, 1951, **43** (4), 905–10.—The laboratory investigation of azeotropes of hydrocarbons with alkane sulphides, disulphides, and thiophenes is described. Graphical correlation of hydrocarbon b.p. and mol per cent sulphide in the corresponding azeotrope give a linear relationship, as does a plot of azeotrope b.p. and log mol per cent sulphide. From the data it is possible to predict azeotrope formation between a hydrocarbon and a sulphide. W. H.

2119. Azeotropes of 2-ethoxyethanol with alkyl benzene. W. F. Kieffer and C. E. Grabiel. *Industr. Engng Chem.*, 1951, **43** (4), 973–5.—Data obtained from distillation studies of 2-ethoxyethanol and a range of seven alkyl benzene are presented. The reliability of the results is indicated by the two methods of graphical correlation adopted. W. H.

2120. Composition of vapours from boiling binary solutions. D. F. Othmer, W. P. Moeller, S. W. Englund, and R. G. Christopher. *Industr. Engng Chem.*, 1951, **43** (3), 707–11.—This work reports a new type of equilibrium still for evaluating vapour–liquid equilibria at super-atmospheric pressures. Vapour–liquid equilibrium data is given for the system ethyl alcohol–water for pressures up to 125 p.s.i.g. The consistency of this data is shown by plots of activity coefficients, relative volatility, and log mol % of one component against the total system pressure. E. J. C.

2121. Compositions of vapours from boiling solutions. W. P. Moeller, S. W. Englund, T. K. Tsui, and D. F. Othmer. *Industr. Engng Chem.*, 1951, **43** (3), 711–17.—Vapour–liquid equilibria are presented at various pressures up to 125 p.s.i.g. for the two systems ethyl ether–ethyl alchol and ethyl ether–water–ethyl alcohol. The data obtained are reported to have been used in the design of an alcohol dehydration column with satisfactory results. E. J. C.

2122. Critical thermal flux on boiling liquids within a large volume. M. A. Stuirikovich and G. M. Polyakov. *Izvest. Akad. Nauk S.S.S.R., Otdel. Tekh. Nauk*, 1951, 652–6.—Crit thermal flux (corresponding to change to film boiling) was determined in laboratory by boiling on a plane elec-heated nichrome surface of dimensions 5 × 0·2 × 300 mm immersed in a large vol of liquid. Crit flux was determined by reddening of plate on heating by A.C. Tests were at atm pressure. Sides and one surface of plate were screened, so that boiling occurred on one side only. Results obtained with heating surface horizontal and facing up were (k.cal/m²/hr × 10^3) H_2O 1730, MeOH 632, EtOH 442, *iso*PrOH 403, C_6H_6 412, Et acetate 354, *n*-heptane 336, aq EtOH (83%) 745. Values for the heating surface facing down were on average 40% lower and 20% lower for vertical situation (for 200 mm side, for 5 mm side, 8%). Results are discussed, with particular reference to their application to steam-heated tubular surfaces. For latter max heat flux is considerably below crit value owing to less effective vapour removal from underside of tube and also owing to irregular heating of the tube perimeter. V. B.

2123. Properties of high boiling petroleum products. L. T. Eby *et al.* *Industr. Engng Chem.*, 1951, **43** (4), 954–60.—Distillation studies of dilute solutions of polynuclear aromatics in high-boiling aromatic and non-aromatic petroleum oils are described. Analysis of the fractions was made by means of ultra-violet absorption spectrometry. The relative volatilities of the solutes are found to be higher in non-aromatic oils than in aromatic oils. A linear relation was found between atmospheric b.p. of a non-aromatic solvent and the log of the relative volatility of polynuclear aromatic solute. W. H.

2124. Rectifying column performance—Effect of intermittent reflux. P. T. O'Leary, J. R. Bowman, and J. Coull. *Industr. Engng Chem.*, 1951, **43** (2), 541–4.—A theoretical study of column performance under intermittent reflux is made, and the predictions are checked experimentally. The conclusion is reached that intermittent reflux operation leads to a mean distillate composition which is slightly heavier than that obtained by continuous reflux. W. H.

2125. A rotary thermal rectifying column. E. S. Byron *et al.* *Industr. Engng Chem.*, 1951, **43** (4), 1002–10.—A new type thermal rectifying column is described. It comprises two concentric tubes, the outer one heated and the inner cooled and rotated. The vapour rises in the annular space. The theory of operation of the still is developed, and performance data are given. The main advantage claimed for the column is that it may be operated at much lower pressures than conventional types. W. H.

2126. Vapour-liquid equilibria in binary systems. N. Alpert and P. J. Elving. *Industr. Engng Chem.*, 1951, **43** (5), 1174–7.—Vapour–liquid equilibrium data at 760 mm Hg are presented for the systems *cis*dichloroethylene–methanol and *trans*dichloroethylene–methanol. The experimental results were found approx to fit the Van Laar and Margules equations. Both systems showed min boiling azeotropes. E. J. C.

2127. Vapour–liquid equilibria in binary systems. D. G. Flom, N. Alpert, and P. J. Elving. *Industr. Engng Chem.*, 1951, **43** (5), 1178–81.—Vapour–liquid equilibrium data at 760 mm Hg are presented for the systems *cis* or *trans*dichlorethylene with methylal, tetrahydrofuran, and *iso*propyl ether. The experimental results do not fit the Van Laar or Margules equations. Vapour pressure–temp relationships were also obtained for the dichloroethylene isomers and *iso*propyl ether. Max b.p. azeotropes were observed in the systems *cis*dichloroethylene–tetrahydrofuran and *trans*dichloroethylene–methylal. E. J. C.

2128. Vapour–liquid equilibria in binary systems. N. Alpert and P. J. Elving. *Industr. Engng Chem.*, 1951, **43** (5), 1182–6.—Binary vapour–liquid equilibrium data are presented for the systems *cis* or *trans*dichloroethylene with ethyl formate, methyl acetate, acetone, and 2-butanone at 760 mm Hg. In some of these systems the experimental results fitted the Van Laar or Margules equations.

The vapour–liquid equilibrium data observed in this and two previous papers (Abs. Nos. 2126 and 2127) are explained on the basis of hydrogen bonding, b.p., dipole moments, and steric factors.

Azeotropic distillation is suggested for separation of the *cis–trans* isomers of dichloroethylene. E. J. C.

2129. Vapour liquid equilibria for the system methyl ethyl ketone–*sec*butyl alcohol. E. H. Amick *et al.* *Industr. Engng Chem.*, 1951, **43** (4), 969–73.—Data for the binary system at total pressures of 760·0 mm and 374·5 mm are presented. The adiabatic–jacketed column still was used. It was not possible to correlate the data by any form of the Duhem equation. W. H.

2130. Vapour liquid equilibrium for the ternary system acetone–chloroform–methyl-*iso*butyl ketone. A. E. Karr *et al.* *Industr. Engng Chem.*, 1951, **43** (4), 961–8.—Acetone and chloroform binary mixtures are of some industrial importance, and extractive distillation has been suggested as a means of separation with methyl *iso*butyl ketone as a solvent. Data are presented, and it is found that ternary data can be satisfactorily predicted from data of the binary systems. W. H.

Absorption and Adsorption

2131. Absorption and Humidification. R. L. Pigford. *Industr. Engng Chem.*, 1951, **43** (1), 41–5.—A review, with ninety-nine references. (Unit operations symposium 1951.) F. M.

2132. Adsorption. B. L. Harris. *Industr. Engng Chem.*, 1951, **43** (1), 46–55.—A review, with 315 references. (Unit operations symposium 1951.) F. M.

Solvent Extraction and Dewaxing

2133. Solvent Extraction. R. E. Treybal. *Industr. Engng Chem.*, 1951, **43** (1), 79–85.—A review with 235 references. (Unit operations symposium 1951.) F. M.

2134. Nitriles as selective solvents. K. W. Saunders. *Industr. Engng Chem.*, 1951, **43** (1), 121–6.—Tests are described on benzene–heptane test mixture with a variety of solvents to establish the selectivity and capacity of the solvent for the extraction of aromatics from petroleum hydrocarbons. The most selective solvents were nitriles of general formula $CN\text{-}(CH_2)_n - x$, where $n = 1$ to 5, $x = CN$, NR_1R_2, OR, SR, and the nature of the R groups is limited. Ternary data are given for various nitriles with benzene–heptane and methyl naphthalene–dodecane systems, and a comparison

is given of dipropionitriles and succinonitrile using a test mixture of dodecane, tetralin, and β-methyl naphthalene. A brief discussion on the relationship between solvent action and structure is included. F. M.

Cracking

2135. Catalytic treating of petroleum fractions. G. Egloff. *Riv. Comb.*, June 1951, **6**, 267–95. (*Societa Chimica Italiane, Milan*, 11.6.51.)—Discusses recent developments in catalytic treating of petroleum fractions. The Platforming process for the production of aromatics and of upgraded motor gasolines is particularly considered.

2136. Fluidization studies of solid particles. C. O. Miller and A. K. Logwinuk. *Industr. Engng Chem.*, 1951, **43** (5), 1220–6.—A study was made of some of the factors governing the fluidization and heat transfer in fluidized beds. The dynamics of the process are dealt with briefly by dimensional analysis. The apparatus used for pressure-drop experiments and that used for heat-transfer measurements are described. Results are shown graphically. E. J. C.

2137. The fluidized bed. R. H. Wilhelm and S. Valentine. *Industr. Engng Chem.*, 1951, **43** (5), 1199–203.—An account is given of the experimental study of a stream of solid particles introduced into a rising gas stream. It was found that fluidized beds were formed as the particle motion changed from cocurrent to countercurrent with respect to the gas. The results are presented graphically. E. J. C.

2138. Houdriforming—a continuous process for reforming petroleum naphthas. C. G. Kirkbride. *Refiner*, 1951, **30** (6), 95–8. (*Joint regional meeting, AIChE and ACS, Tulsa*, May 16, 1951.)—A discussion on pilot-plant work carried out by the Houdry Process Corporation. Houdriforming is a catalytic process for reforming petroleum naphthas to aromatic concentrates and high-octane gasoline. The process is capable of producing maximum yields of benzene, toluene, and xylene. Good catalyst characteristics are claimed, but no details are given. R. W. G.

2139. Midget fluid catalytic cracking units. H. W. Grote, J. Hoekstra, and G. T. Tobinson. *Industr. Engng Chem.*, 1951, **43** (2), 545–50.—It has been found possible to set up laboratory-scale fluid catalytic cracking units which approach closely to commercial operating conditions. There is a great economy in manpower and costs as compared to the semi-commercial pilot plant. Hitherto the fixed-bed catalysis has limited the scope of laboratory scale work. Adopting the circulating fluid catalyst technique, weight hourly, space velocities of 1 to 3 and catalyst to oil weight ratios of 3 to 10 have been used in cracking investigations. W. H.

2140. Pressure feeder for powdered coal or other finely divided solids. K. R. Barker, J. S. Sebastian, and L. D. Schmidt. *Industr. Engng Chem.*, 1951, **43** (5), 1204–9.—This paper reports the apparatus, experimental procedure, and results obtained during development work carried out to find a continuous method of charging finely divided coal to a pressurized gas regenerator. E. J. C.

Hydrogenation

2141. High pressure fixed bed catalytic unit. G. B. Arnold, F. P. Frascati, and N. D. Carter. *Industr. Engng Chem.*, 1951, **43** (4), 1013–18.—The hydrogenation of a high sulphur virgin gas oil in a pilot unit is described. The plant is designed to handle charges with a wide range of visc, composition, etc. W. H.

2142. Vapour phase hydrogenation of light and heavy oils. M. L. Wolfson, M. G. Pelipetz, A. D. Damick, and E. L. Clark. *Industr. Engng Chem.*, 1951, **43** (2), 536–40.—Hydrogenation of aromatic oils over catalysts of chromium–molybdenum–zinc on activated fullers' earth at a pressure of 9000 p.s.i. and at temp of 475° and 500° C has been carried out successfully on a small scale in a reactor 2 inches O.D. and 4 ft long. The product contained 46·6% gasoline, and 2·8% hydrogen was consumed (percentages on feed). W. H.

Isomerization

2143. Allyl alcohol—Isomerization of propylene oxide over a chromic oxide catalyst. L. G. Lundsted, E. C. Jacobs, E. J. Schwoegler, and T. H. Vaughn. *Industr. Engng Chem.*, 1951, **43** (3), 728–30.—The catalytic vapour-phase isomerization of propylene oxide is reported using various chromic oxide base catalysts. The experiments showed that a chromic oxide gel-type catalyst was the most efficient and that for the same catalyst and same rate of feed of propylene oxide per litre of catalyst space per hr at 350° C, the main product was allyl alcohol, while above 350° C the main product was propionaldehyde. E. J. C.

2144. Houdriforming. C. G. Kirkbride. *Oil Gas J.*, 5.7.51, **50** (9), 60.—A non-regenerative process for reforming petroleum naphthas and effect of changing catalyst properties is discussed; a pilot plant being in an advanced state of development. Essentially no hydrocracking occurs, and substantially pure hydrogen is produced. Catalysts are not affected by sulphur compounds, including thiophene.

Tables show properties of base stocks, operating conditions for aromatic production, and for gasoline upgrading.

Reactions involved are theoretically considered. G. A. C.

2145. Lower paraffin hydrocarbons—catalytic conversion by boron fluoride with hydrogen fluoride. E. C. Hughes and S. M. Darling. *Industr. Engng Chem.*, 1951, **43** (3), 746–50.—The report describes the work carried out and results obtained by contracting propane, *n*-butane, *n*-pentane, and *n*-heptane with boron trifluoride and hydrogen fluoride under pressures of up to 350 p.s.i.g. The results showed that the extent to which disproportionation occurred was dependent upon the temp, and that effectiveness of the catalyst was influenced by the presence of olefins and hydrogen. E. J. C.

Chemical and Physical Refining

2146. Acid treatment of shale gasoline. Pt I. Hydrolysis of the acid sludge. R. C. Mathews and G. E. Mapstone. *J. Inst. Petrol.*, 1951, **37**, 147–57.—The quantity of acid extracted by hydrolysis of the acid sludge is independent of the proportion of water used. The total tar content was found to decrease with increasing acid concentrations above 6N. The sp. gr. of both the hydrolysed acid and the insoluble tar increased with increasing acid strength. The hydrolysed acid precipitated tars spontaneously, freshly precipitated tars being soluble in a number of solvents, but on standing these tars decomposed and were only sparingly soluble. The hydrolysed acid corroded mild-steel pipe appreciably above 200° F, a max rate being obtained with 7N acid. Sulphuric acid inhibited with tar bases condensed with benzaldehyde showed corrosion rates at 200° F comparable with hydrolysed acid. Sulphuric acid inhibited with tar bases showed a higher rate of corrosion and did not exhibit the max value with acid concentration. A. R. W. B.

2147. Separation of sulphur and aromatics from petroleum. E. C. Hughes, W. E. Scovill, C. H. Whitacre, R. B. Faris, J. D. Bartleson, and S. M. Darling. *Industr. Engng Chem.*, 1951, **43** (3), 750–3.—This report describes the apparatus, procedure, and operating conditions for selective removal of sulphur and aromatics from distillates and crude oils, using hydrogen fluoride and boron trifluoride as solvents at operating pressures up to 380 p.s.i.g. Apart from economic considerations, the results given in this short paper indicate the feasibility of this process for removal and/or recovery of sulphur and aromatics from petroleum. E. J. C.

2148. Sweetening and desulphurization of light petroleum products. Pt VIII—Miscellaneous desulphurization process. V. A. Kalichevsky. *Refiner*, 1951, **30** (6), 135–37. (See Abs. Nos. 1042, 1476, 1875–9.)—This last article of the series briefly discusses the use of solvents and anhydrous chemical reagents for desulphurization. Lists of twenty-seven solvents and eighty-five anhydrous chemical reagents are given, together with twenty-three literature references. R. W. G.

Special Processes

2149. Carbon black. G. Kiddoo. *Chem. Engng*, 1951, **58** (3), 104–8.—The development of the industry from 1935 is traced, and the processes used and properties required are described in detail. Future trends expected are an increase in production by the furnace process; a decrease in the use of natural gas as raw material as the cost rises in U.S.; an increase in electrostatic recovery from flue gases as the industry moves from natural-gas fields towards the towns. The incorporation of carbon black in latex prior to coagulation reduces power costs, and may cause rubber and carbon-black factories to be built close together. D. H.

2150. More British carbon black. Anon. *India Rubber J.*, 1951, **120** (24), 946.—An outline is given of the recently announced plans for the expansion of the Cabot Carbon Ltd. plant at Ellesmere Port; present production will be doubled to give total capacity of 40 million lb/year. Using liquid hydrocarbons, *e.g.*, petroleum residues, as raw material, the new unit will produce primarily high-abrasion furnace grades of carbon black, best suited to the full reinforcement of rubber. C. N. T.

2151. The production and distribution of petrol from coal and from imported crude petroleum. P. N. Jategan. *J. chem. metall. min. Soc. S. Africa*, Apr. 1951, **51** (10), 297–312.—The hydrogenation and Fischer–Tropsch processes for the conversion of coal into oil are described. The production cost for 1000 cu. ft. of synthesis gas, in South Africa, is given for the following methods: the Kopper (suspension method), 15·33*d*; the Winkler (fluidized-bed method), 16·74*d*; the Lurgi (fixed-bed method), 18·40*d*. The mechanism of each method is described, and gasification and synthesis economics are given and discussed. Estimated cost for the three plants and their operating costs are given. The Kopper process is considered best for South Africa. The estimated cost of the Kopper plant for 100,000,000 gal/year of synthetic petrol is £27,000,000. Cost per gal would be 1*s.* 5*d*. For the same amount of natural petrol from imported crude oil the capital cost of a refinery in the Rand, and a pipeline from the Coast, would be £11,500,000. Cost per gal would be 10½*d*. Details of specifications, capital cost, and operating costs of the pipeline, and capital and working costs of the refinery are shown. As the proposed local synthetic petrol industry will necessitate a change in the present distribution system, a rationalized scheme for refining and distribution is submitted. This scheme is designed to stimulate the development of such an industry and at the same time safeguard the interest of the consumer. W. H. C.

2152. Fundamentals and performance of gravity separation. A. C. Ingersoll. *Refiner*, 1951, **30** (6), 106–18.—An extensive literary review discussing the process of gravity separations, including both possibilities of density difference. Emphasis has been made on oil–water separations. The article is introduced by a brief reference to the early work of Newton and Stokes.

Eighty-four references to the literature are given on the general aspect for the petroleum industry, twenty references on mathematical and physical considerations of the motion of particles immersed in fluid, fifteen references to engineering papers on sedimentation, density currents, and turbulence, and thirty references to papers on mechanical analysis of suspensions (particle-size distribution). R. W. G.

2153. Patents. Ger.P. 801,329. G. Free and W. Simon. Bradische Anilin and Soda Fabrik (I. G. Farbenindustries A.G. "In dissolution"). Process for the production of unsaturated hydrocarbons from alcohols. 2.10.48. P 1081 F (4.5.50).

Fr.P. 962,768. Standard Oil Development Co. and T. C. Main. Catalytic production of hydrocarbons from CO and H_2. 2.3.48, 14.6.50 (Prior. America 9.5.47).

Fr.P. 963,881. Standard Oil Development Co. and A. Voorhies, Jr. Catalytic synthesis of hydrocarbons from CO and H_2. 25.3.48, 24.7.50. (Prior. America 1.7.47.

Fr.P. 964,636. J. C. Dart, assr. to Standard Oil Development Co. Catalytic synthesis of hydrocarbons from CO and H_2. 13.4.48, 21.8.50. (Prior. America 30.6.47.)

Fr.P. 957,261. Standard Oil Development Co. and M. A. Moserman. Catalyst for the Fischer–Tropsch process. 15.12.47, 15.2.50. (Prior. America 20.12.46.)

Fr.P. 959,193. C. E. Hemminger, assr. to Standard Oil Development Co. Production of hydrocarbons from CO and H_2. 2.1.48. 23.3.50. (Prior. America 15.1.47.)

Fr.P. 961,524. C. N. Kimberlin, Jr., assr. to Standard Oil Development Co. Production of hydrocarbons from CO and H_2. 20.2.48, 12.5.50. (Prior. America 20.3.47.)

Fr.P. 964,635. A. Voorhies, Jr., assr. to Standard Oil Development Co. Regeneration of catalysts containing carbon from the hydrocarbon synthesis from CO and H_2. 13.4.48, 21.8.50. (Prior. America 5.6.47.)

Fr.P. 959,599. J. A. Phinney, B. S. Page, and G. R. Ayton, assrs. to Stanolind Oil and Gas Co. Synthetic production of hydrocarbons from CO and H_2. 14.1.48, 31.3.50. (Prior. America 14.1.47.)

Fr.P. 960,151. G. B. Arnold and H. V. Hess, assrs. to Texaco Development Corp. Synthetic production of hydrocarbons from CO and H_2. 24.1.48, 13.4.50. (Prior. America 1.2.47.)

Fr.P. 962,155. M. W. Kellogg Co. and H. G. McGrath. Separation of compounds containing oxygen and hydrocarbons from the reaction mixture from the catalytic hydrogenation of carbon monoxide. 26.2.48, 2.6.50. (Prior. America 27.2.47.)

Fr.P. 959,374. N. V. De Bataafsche Petroleum Maatschappij and L. C. Fetterly. Separation of normal straight-chain aliphatic hydrocarbons from their mixtures with branched aliphatic and cyclic hydrocarbons. 6.1.48, 28.3.50. (Prior. America 7.1.47.)

R. T.

PRODUCTS

Chemistry and Physics

2154. Acetaldehyde, propionaldehyde, and *n*-butyraldehyde. T. E. Smith and R. F. Bonner. *Industr. Engng Chem.*, 1951, **53** (5), 1169–73.—Data are presented on the refractive index, density, and vapour pressure of pure samples of the above aldehydes over the following temperature ranges: (*a*) Density, 0° to 30° C; (*b*) Refractive index—(i) acetaldehyde, 5° to 17° C, (ii) propionaldehyde, 5° to 20° C, (iii) *n*-butyraldehyde, 5° to 20° C; (*c*) vapour pressure—(i) acetaldehyde, 0° to 20·5° C, (ii) propionaldehyde, 18° to 48° C, (iii) *n*-butyraldehyde, 40° to 75° C.

Vapour pressures were also plotted in the form of a Cox's chart for the range −50° to 120° C. E. J. C.

2155. Aliphatic esters of cellulose. C. J. Malm, J. W. Mench, D. L. Kendall, and G. D. Hiatt. *Industr. Engng Chem.*, 1951, **43** (3), 684–8.—This work reports the experimental and analytical work involved in the preparation of triesters of cellulose in the series acetate to palmitate, all having the same degree of polymerization, by using the acid chloride–pyridine procedure. E. J. C.

2155a. Aliphatic esters of cellulose. C. J. Malm, J. W. Mench, D. L. Kendall, and G. D. Hiatt. *Industr. Engng Chem.*, 1951, **43**, (3), 688–91.—M.p. behaviour, moisture sorption, density, tensile strength, refractive index, solubilities, and specific rotation for a series of cellulose triesters from acetate to palmitate are reported. E. J. C.

2156. Assumptions of the B.E.T. theory. W. G. McMillan and E. T. Teller. *J. Phys. & Colloid Chem.*, 1951, **55**, 217–21.—A qualitative discussion is given of two simplifying assumptions of the B.E.T. theory and the consequence of their replacement by a more exact approach. An isotherm equation, valid in the region of multilayer absorption, is obtained which takes account both of the effect of the surface energy of the absorbate and of the extension of the absorbent attractive forces beyond the first layer. The difference between this equation and one of identical functional form obtained earlier by Hill are usually negligible numerically, but the present treatment supplies the qualitative evaluation necessary for a justification of Hill's model. N. T.

2157. Calculation of diffusion penetration curves for surface and grain boundary diffusion. P. C. Fisher. *J. appl. Phys.*, 1951, **22**, 74–7.—Diffusion in solids is known to occur along grain boundaries and over free surfaces more rapidly than through the interior of the crystals. In order to facilitate quantitative investigation of grain boundary and surface diffusion, a mathematical analysis of the problem has been completed, assuming the grain-boundary diffusion is analogous to the diffusion of heat along a thin copper foil imbedded in cork. The calculated diffusion is shown to agree with the experimentally determined grain boundary self-diffusion of silver.

N. T.

2158. Catalysts for reforming of propane. J. J. S. Sebastin and C. H. Riesz. *Industr. Engng Chem.*, 1951, **43** (4), 860–6.—The poisoning of catalysts used in hydrocarbon reforming by sulphur has been investigated. Catalyst activity is measured in terms of "volume expansion" analogous to the "contraction" used conventionally in the Fischer–Tropsch synthesis. The effect of sulphur is determined by evaluation of catalyst activity in presence of specified concentrations of hydrogen sulphide in the reactants. The experiments show that a nickel sulphide on alumina catalyst was most resistant to sulphur poisoning, and that nickel in practically all forms was the most active catalyst substance.

W. H.

2159. Coal hydrogenation catalysts. S. Weller and M. G. Pelipetz. *Industr. Engng Chem.*, 1951, **43** (5), 1243–6.—Work is reported on the influence of catalyst distribution on its effectiveness in promoting the hydrogenation of coal. Catalysts used were ammonium molybdate, $NiCl_2$, and $FeSO_4$. The results indicated that by properly distributing the catalyst, the effectiveness of many coal-hydrogenation catalysts could be improved.

E. J. C.

2160. Diffusion coefficients of organic liquids in solutions. R. L. Olson and J. S. Walton. *Industr. Engng Chem.*, 1951, **43** (3), 703–6.—A method is proposed for estimating diffusion coefficients of organic liquids in water solution using surface-tension measurements. The proposed correlation fits available data with an average accuracy of 2%. Approx methods are also suggested to allow for variation of diffusivity with temp and in the presence of different solvents.

E. J. C.

2161. Emissivity calculations for diatomic gases. S. S. Penner. *J. appl. Mech.*, Mar. 1951, **18**, 53–8.—An approx method for estimating radiant-heat transfer from gaseous emitters has been developed. An average absorption coefficient is used for an effective width of an entire vibration–rotation band. The procedure for determining an average absorption coefficient in terms of the integrated absorption can be justified, approx, for very large total pressures when the spectral half-width is no longer small compared with rotational spacing. Because of this limitation, it is to be expected that the procedure proposed will be particularly useful only in estimating gaseous emissivities for emitters in high-pressure combustion chambers. Nevertheless, it appears that the simplified procedure yields reasonable results even at relatively low total pressures. A comparison of calculated and observed emissivities for CO at atmospheric pressure shows satisfactory agreement, especially at large optical densities.

Representative emissivity calculations over a wide temperature range are described. Emissivity calculations on CO, NO, HF, HCl, HI, and HBr can be carried out rapidly using recently published data on these gases.

N. T.

2162. Electrical conductivity method for measuring self-diffusion of metals. *J. appl. Phys.*, 1950, **21**, 1224–5.—A proposed method for the measurement of self-diffusion in metals is by measurement of the contact conductance of an interface between two metallic spheres or hemispheres.

N. T.

2163. Experiments on dehydrochlorination of chlorinated paraffin waxes. A. Girelli and C. Siniramed. *Riv. Comb.*, June 1951, **6**, 296–9.—Experiments are reported on the dehydrochlorination of chlorinated paraffin waxes (Cl content about 30 to 33%). Dehydrochlorination has been carried out by batch decomposition at 300° C.

Heavy olefins have been obtained (iodine value about 130 to 150), which may be used as raw material for the preparation of polymer lubricating oils.

(Authors' abstract.)

2164. Extraction of lactic acid from water solution. W. P. Patchford, E. H. Harris, C. H. Fisher, and C. O. Willits. *Industr. Engng Chem.*, 1951, **43** (3), 778–81.—In this article brief results are presented for the extraction of lactic acid from water by various combinations of amines with different organic solvents. E. J. C.

2165. Fluid flow through porous media. L. Green, Jr., and P. Duwez. *J. appl. Mech.*, Mar. 1951, **18**, 39–45.—A method is outlined for correlating experimental data obtained in the study of the flow of gases and liquids through porous metals. The correlation, based on Forcheimer suggestion, is that the pressure gradient attending the flow of a liquid through a porous medium can be expressed as a function of flow rate by a simple quadratic equation.

An equation of this type defines two length parameters necessary for characterization of a porous structure and permits a general definition of the Reynold's number for a structure of arbitrary complexity. N. T.

2166. Hydrogen transfer over silica–alumina catalyst. R. W. Blue and C. J. Eagle. *Industr. Engng Chem.*, 1951, **43** (2), 494–501.—The transfer is investigated of hydrogen from naphthenes to olefins, in this case by a study of the reaction of *cis*-decalin and tetralin and 1-butene over silica–alumina catalysts. The effect of catalyst composition, space velocity, and temp on the composition of reaction products are detailed. By use of a radioactive olefin the source of the catalyst deposit is traced. At low conversions olefins are largely responsible for the deposit, but aromatics contribute to the deposit at higher conversions. W. H.

2167. Inflammability ranges of propane–air mixtures under reduced pressure. R. Delbourgo and P. Laffitte. *Nature*, 1951, **167**, 985.—Ignition of propane–air mixtures by a single spark gave the normal pressure/composition type of curve. A series of sparks of total duration <1 sec gave a curve the shape of which suggested an overlapping system of two different ranges, due to different mechanisms of combustion. Dilution of the reaction mixture with nitrogen led to the separation of combustion limits into two parts at a nitrogen/oxygen vol ratio of 9 : 1. H. C. E.

2168. Kinetics and mechanism of solid phase reactions. E. A. Gulbransen and R. Ruka. *Industr. Engng Chem.*, 1951, **43** (3), 697–703.—The processes involved in the formation of films of multiple oxides on pure iron are considered from both the kinetic and thermodynamic points of view. Thermodynamic calculations show that the solid phase reaction $Fe_3O_4 + Fe \longrightarrow 4FeO$ is favourable above 570° C, whilst the reaction $4Fe_2O_3 + Fe \longrightarrow 3Fe_3O_4$ and the direct gas phase oxidation reactions are favourable over a wide range of temp. Use was made practically of electron-diffraction methods in studying these solid-phase reactions under vacuum conditions. E. J. C.

2169. Latent heats of vaporization nomograph. T. H. Arnold and P. K. Raiford. *Chem. Engng*, 1951, **58** (4), 138–9.—A nomograph covers a range of substances such as acetone, benzene, *n*-butane, *m*-cresol, pyridine, nitrogen tetra-oxide more accurately than by the empirical relationships presented by Meissner and by Klein. D. H.

2170. Maxwell's Demon cannot operate. Information and entropy. I. L. Brillouin. *J. appl. Phys.*, 1951, **22**, 334–7.—The myth of Maxwell's Demon disobeying the second law of thermodynamics is exploded. Consideration of the cycle Negentropy $\longrightarrow$ Information $\longrightarrow$ Negentropy shows that the smallest possible amount of negative entropy needed for a scientist to make an observation is Boltzmann's constant K. N. T.

2171. Maxwell's Demon cannot operate. Physical and information. II. L. Brillouin. *J. appl. Phys.*, 1951, **22**, 338–43.—Using the laws of statistical thermodynamics to define entropy, the definition of information reduces to a problem in Fermi–Dirac statistics. These definitions allow the entropy of a message to be defined, and the information contained in the message can be connected with a decrease in entropy in the system.

The results show that Shannon's "entropy information" corresponds to an equal amount of negative entropy in the physical system. N. T.

2172. Isobaric heat capacities at bubble point. T. J. Connodly, B. H. Sage, and W. N. Lacy. *Industr. Engng Chem.*, 1951, **43** (4), 946–50.—Heat capacities of *n*-hexane, methyl *cyclo*pentane, and *n*-octane are determined in a series of calorimetric measurements, temp. rise due to the addition of a known quantity of electrical energy being determined. Other thermodynamic properties are calc. from the experimental data. W. H.

2173. Reverse separation in fractionation pumps. K. Hickman. *Rev. sci Instrum.*, 1951, **22**, 141–6.—The relative volatilities of mixtures of liquids increase surprisingly at low rates of distillation. A consequence is that organic liquids release volatiles into high vacuum apparatus more readily than would be deduced from measurements made at usual pressures of, say, 1 to 100 μ. The composition of condensate in an oil-filled diffusion pump is found to be a function of the position in the pump, the lightest constituents straying to the high vacuum end. As an example, Octoil (2-ethyl hexyl phthalate) contaminated with less than 1% butyl phthalate in the last boiler of a three-stage pump was found to pass vapour through the high-vacuum entrance as though the boiler had contained 27% butyl phthalate.

To epitomize the situation, a vapour pump is a specialized form of still with two exits. The intention of the designer, expressed in the geometry of the pump, is to force the lighter molecules to one exit, but molecular perversion causes them to wander to the other. The effect is probably unimportant except where the highest vacuums are required, though it does point to the desirability of thorough pre-purification of the pump oils; the task of fractionation, before and during use, is harder than we had supposed. (Author's abstract.) H. C. E.

2174. Rheological properties of a lubricating grease. S. R. Singleterry and E. E. Stone. *J. Coll. Sci.*, 1951, **6**, 171–89.—When the phenomena of flow in a capillary are separated from effects such as piston drag, entrance losses, and temp increases, a shear-stable grease behaves substantially as a Bingham plastic, the flow of which can be specified in terms of yield value and mobility.

The apparatus comprises two vertically opposed cylinders separated by orifice plates containing 0·0135-inch holes. Pistons fitting closely in the cylinders are held stationary, and the cylinder assembly is moved in reciprocating motion. Consistency is measured by removing the lower piston support and forcing grease from the upper to the lower cylinder by applied loads on the upper piston. The effect of errors arising from temp increase, end effects, and entrance losses are discussed. A synthetic grease containing 16% lithium stearate, 1% sorbitan mono-oleate, 0·2% 4-*tert*-butyl-2-phenylphenol in di(2-ethylhexyl) sebacate was used.

The Bingham yield value and mobility of the grease are computed by a graphical procedure based on the Buckingham equation $V = (1 - 4p/3P + p^4/3P^4)\pi a^4 mP/8L$, where V = vol rate of flow through a tube length L and radius a; P = pressure drop; p = yield pressure at which flow begins; and m = mobility of the grease $= 1/\eta_\infty$. This treatment permits the computation of the yield value and mobility from data for flow at two pressures without resort to trial-and-error operations.

The yield value so obtained is in reasonable agreement with direct measurements. The limiting apparent visc approached at high flow rates (η_∞) is two to five times the η of the sebacate fluid in the grease. H. C. E.

2175. Observation of spiral growth-steps in *n*-paraffin single crystals in the electron microscope. I. M. Dawson and V. Vand. *Nature*, 1951, **167**, 476.—Small crystals of *n*-hexatriacontane $C_{36}H_{74}$, grown from a solution in petroleum ether, were shadow-cast with Pd and examined in an electron microscope. It can be seen that the crystal face consists of a series of molecular steps. The crystal, however, does not grow in a series of closed terraces, for the molecular step edge runs in a continuous spiral from the apex to the base. Hence during growth fresh molecules can always condense on a monomolecular edge, and successive molecular edges do not have to be initiated on the growing crystal face. H. C. E.

2176. Oxidation of olefins representing some structural units of GR–S. W. C. Warner and J. Reid Shelton. *Industr. Engng Chem.*, 1951, **43** (5), 1160–4.—The oxidation of 1-phenyl-4-hexene, 1-phenyl-3-pentene, and 2-octene was studied because these compounds are structurally related to GR–S. A probable chemical mechanism was

proposed which may apply to similar problems such as oxidation of lubricating oils. E. J. C.

2177. Peroxides from turpentine. G. S. Fisher and L. A. Goldblatt. *Industr. Engng Chem.*, 1951, **43** (3), 671–4.—Preliminary investigational work is reported for the production of peroxides from terpene hydrocarbons and hydrogenated terpene hydrocarbons obtained from turpentine. Those peroxides produced showed great possibilities for use as catalysts in the production of "cold rubber." As most of the present peroxides used in the manufacture of synthetic rubber are based on benzene, development of the terpene hydroperoxides would involve a saving of substantial quantities of benzene, which is in short supply. E. J. C.

2178. Physical properties of methanol–water system. C. Carr and J. A. Riddick. *Industr. Engng Chem.*, 1951, **43** (3), 692–6.—Density and sp. gr.–composition relationships are given for the water–methanol system at 25°, 30°, and 40° C. The shrinkage–composition relationship for the same system at 25° C is also tabulated. E. J. C.

2179. Some criteria for commercial spectrometers. J. G. Reynolds *J. Inst. Petrol.*, 1951, **37**, 125–34.—The infra-red criteria of hypothetical plant and research instruments are discussed. A. R. W. B.

2180. The absorption spectra of molecules in the vacuum ultra-violet. W. C. Price. *J. Inst. Petrol.*, 1951, **37**, 106–9.—Experimental aspects of the spectroscopy of the vacuum ultra-violet are described briefly, and the nature of the spectra observed in this region is discussed. A. R. W. B.

2181. The infra-red and Raman frequencies of hydrocarbon groupings. N. Sheppard. *J. Inst. Petrol.*, 1951, **37**, 95–106.—The nature of the information about molecular vibration frequencies provided by infra-red and Raman spectra is described. Characteristic features in the spectra of some of the main types of hydrocarbon groupings are considered. A. R. W. B.

2182. Industrial applications of absorption spectroscopy. Spectroscopic panel of the Hydrocarbon Research Group of the Institute of Petroleum. *J. Inst. Petrol.*, 1951, **37**, 109–25.—The basic principles of the application of absorption spectroscopy to industrial problems are given and some varied examples described. A. R. W. B.

2183. Molecular orbital treatment of the ultra-violet spectra of *cyclo*-otatetraene. Y. Morl, I. Tanaka, and S. Shida. *Bull. Chem. Soc. Japan*, Nov. 1950, **23** (5), 168.—The energy levels of the *cyclo*-octatetraene molecule, assuming the symmetry as D_{4h}, have been calculated by Goeppert, Mayer, and Sklar's method. It is shown that the ground state of *cyclo*-octatetraene may be diamagnetic, and that the wavelength of the absorption spectra calculated is approx in agreement with the experimental results. W. H. C.

2184. Suitable hydrocarbon for oil–water dispersion measurements. O. S. Mills. *Nature*, 1951, **167**, 726.—Measurement of interfacial phenomena and properties of emulsions is usually complicated by the polarity of the oil and its difference from that of the aqueous phase. The "weighting" of an oil (*e.g.*, $CHBr_3$ in white oil) is not usually satisfactory.

3-3′-ditolyl has been used with good results as an oil phase. Some of its physical props are :—

Temp °C	20	25
Density d_4^t	1·0013 ± 0·0001	0·9989 ± 0·0003
η centipoise	7·25 ± 0·03	5·90 ± 0·02
n_D	1·5962 ± 0·00016	1·5930 ± 0·00017
γ dynes/cm	39·0 ± 0·5	
Dipole moment	zero	
Dielectric const		2·51

Methods of preparing 3-3′-ditetyl are described. H. C. E.

2185. Thermodynamic properties of propylene. L. N. Canjar, M. Goldman, and H. Marchman. *Industr. Engng Chem.*, 1951, **43** (5), 1186–93.—Pressure–vol–temp

relationships taken from the literature were used to accurately calculate pressure-enthalpy relationships of propylene over the range −40° to 480° F and up to 200 atm. The data are presented in tabular and graphical form. E. J. C.

2186. Thermochemistry for the petroleum industry. Pt XVI. Five pointed Lagrangian interpolation coefficients for transforming thermochemical values on the Kelvin to other thermometric scales. K. A. Kobe and R. E. Pennington. *Refiner*, 1951, **30** (6), 143–4. (See Abs. No. 1896.)—The use of the above-cited method is illustrated, and tables of coefficients for converting values for °K to °C, °R and °F are given. R. W. G.

2187. Volumetric and phase behaviour of the methane-hydrogen sulphide system. H. H. Reamer *et al.* *Industr. Engng Chem.*, 1951, **43** (4), 976–81.—The molal volumes of four mixtures of methane and hydrogen sulphide at pressures up to 10,000 p.s.i. in a temp range 40° to 340° F have been determined, together with the composition of the co-existing phases throughout the heterogeneous region. W. H.

Analysis and Testing

2188. A superposition analysis of the turbulent boundary layer in an adverse pressure gradient. D. Ross and G. M. Robertson. *J. appl. Mech.*, Mar. 1951, **18**, 95–100.—As an interim solution to the problem of the turbulent boundary layer in an adverse pressure gradient, a superposition method of analysis has been developed. The velocity profile is considered to be the result of two effects: the wall shear stress and the pressure recovery. Super-imposition yields an expression for the velocity profiles which approx measured distributions. The theory leads to more reasonable expressions for the wall shear-stress coefficient. N. T.

2189. Extrapolation of octane numbers above 100. J. F. Deters. *Refiner*, 1951, **30** (6), 127–9.—A new single method for relating the combustion data obtained as *iso*-octane + ml T.E.L. to octane No. for both Motor and Research methods is presented. No secondary standards are required, correlation being obtained by means of an experimentally determined curve which is given. The O.N. equivalents of *iso*-octane + T.E.L. are higher for the Motor method, and with the Research method the extrapolation may not be affected beyond 106·5 O.N. R. W. G.

2190. Gravity determination of heavy petroleum products. H. G. Smith. *Oil Gas J.*, 21.6.51, **50** (7), 341.—No. 76 in the Refiners' Notebook series describes the double-dilution method of gravity determinations, and a table shows practically all cases for which the method may need to be applied.

Accuracy is better than one-half of direct ASTM method. G. A. C.

2191. The particle size analysis of fluid cracking catalysts. Pt I. F. E. Ivey, Jr. *Refiner*, 1951, **30** (6), 99–103.—The first of a series of three articles presenting a manufacturer's method for size analysis of powdered catalyst as used in fluidized cat cracking processes. The method of taking samples and uniformity of sieves for use for sizes above 80 μ is discussed in detail. Indication of difficulty in obtaining entirely uniform and similar sieves is given and reference made to pretreatment of samples by blowing with 60% humid air to overcome surface electrical charges on the particles, which interferes with screening. R. W. G.

2192. Resistance of wool oils to oxidation in storage. Anon. *Amer. Dyestuff Rept.*, 1950, **39** (26), 911.—A description is given of the apparatus, materials, specimens, and test procedure used in an accelerated method (three weeks at 120° F) for evaluating the oxidation of wool oils on fabric. C. N. T.

2193. Rotary condenser fractionating vacuum still. F. C. Benner, A. Dinardo, and D. J. Tobin. *Industr. Engng Chem.*, 1951, **43** (3), 722–7.—A report is presented of a rotating condenser still, primarily for use at high vacuum, but which was evaluated at atmospheric pressure. Data are presented for the operation of the still in the range

0·005 to 1·5 mm of Hg using the systems *n*-hexadecane–1 hexadecane and *m*- and *p*-tricresyl phosphates. Pressure drop from still to column head was of the order of 0·5 mm Hg at these low operating pressures.

Enrichments corresponding to eleven theoretical plates at atmospheric pressure, and eighteen theoretical plates in the low-pressure range were obtained for a glass column length of 44 inches, 32 inches of which were heated electrically. E. J. C.

2194. Viscosity of fire-fighting foam. C. S. Grove, G. E. Wise, W. C. Marsh, and and J. B. Gray. *Industr. Engng Chem.*, 1951, **43** (5), 1120–2.—Data are presented for the effect of pressure, rate of shear, and ratio of air to water on the apparent visc of fire-fighting foam. The experiments were carried out in a flow-type viscometer, which is described together with the foam-generation equipment. E. J. C.

Crude Oil

2195. Laboratory investigation on testing crude oil emulsions. G. M. Davis and R. G. Crippen. *Oil Gas J.*, 5.7.51, **50** (9), 64.—Tests demonstrating the utility of a demulsifying agent for Gulf Coast, Mid-Continent, and heavy Californian type crudes are discussed. Initial colour changes on shaking the oil with the agent give an indication of speed of the agent and its effectiveness.

Eight types of demulsifiers were tested. Cost of treating emulsified oils is about $0·035/brl. G. A. C.

Engine Fuels

2196. Anti-knock antagonists. H. K. Livingston. *Industr. Engng Chem.*, 1951, **43** (3), 663–71.—Certain compounds such as organic halides, peroxides, silicanes, etc., were investigated as antagonists to anti-knocks. It was found that the compounds most harmful to the anti-knock efficiency of T.E.L. were, in order, phosphates, phosphites, silicates, silicanes, arsines, mercaptans, disulphides, sulphides, thiophenes, and organic halides. Although iron and nickel carbonyls showed similar loss of efficiency to T.E.L. as an anti-knock in the presence of these compounds, other anti-knocks such as tetrabutylin and *n*-methylaniline were apparently differently affected.

On the basis of the observed facts, a mechanism of anti-knock action is proposed involving the theory of chain reactions. E. J. C.

2197. Gasoline survey for summer 1950. H. McD. Chantler, P. B. Seely, and R. G. Draper. *Dept. Mines and Technical Surveys, Mines Branch, Canada, No.* 112, Feb. 1951.—This report gives the results of analyses of 118 samples of gasolines, representing thirty-seven brands collected in July 1950 in eleven principal distributing cities and includes, for the first time, five samples from St John's City, Prince Edward Island, Newfoundland. ASTM research knock-ratings are included for the first time and are six or seven O.N. higher than by the Motor method for group 1 gasolines. The average knock rating of both group 1 and group 2 gasolines by the Motor method was significantly higher in 1950 than in 1948. There has been comparatively little change in the volatility of both groups since 1948. A summary of data of gasoline analyses by groups for summers 1937–50 is included. W. H. C.

2198. Composition of Fischer–Tropsch diesel fuel. C. C. Ward, F. G. Schwartz, and N. G. Adams. *Industr. Engng Chem.*, 1951, **43** (5), 1117–19.—This work reports the composition of a synthesized fuel obtained using carbon monoxide and hydrogen by the Fischer–Tropsch process at 390° F and 150 p.s.i. with a cobalt catalyst. The approx volumetric composition of the fuel (boiling range 380° to 592° F) was found to be paraffins 88%, polar compounds 2%, α-type olefins 1·5%, and internal-type olefins 8·5%. Selected properties were obtained after fractionation into 177 samples, among which the Cetane No. was found to vary from 60 to 100+. The original fuel had a Cetane No. of 80. E. J. C.

2199. Harmless diesel exhaust fumes. Anon. *Gas Oil Pwr*, 1951, **46**, 132.—Analysis of the exhaust gases from: (1) diesel engine using oil, (2) petrol engine using com-

mercial petrol, (3) petrol engine using leaded fuel, for CO, CO_2, O_2, and N_2 are given. The exhaust gas from the diesel contained no CO.

Experiments are also described on the contamination (detected by smell and taste) of foodstuffs when exposed to exhaust gases as above. H. C. E.

2200. Patent. Fr.P. 962,977. Araber Trust and G. Doelter. Treatment of liquid propellants for combustion engines. 9.3.48, 26.6.50. (Austrian Prior. 25.6.47.) R. T.

Gas Oil and Fuel Oil

2201. Stability of fuel oils in storage. R. B. Thompson, J. P. Chenicek *et al.* *Industr. Engng Chem.*, 1951, **43** (4), 935–9.—The effect of nitrogenous compounds on the stability of fuel oils has been investigated. Experiments show that pyrroles promote sludge formation, but that substituted pyridines and quinoline have little effect. Acid treatment of fuel oils will improve the stability by removal of the nitrogen compounds. W. H.

Lubricants

2202. The problem of lubrication. K. Kachlik. *Nafta*, Mar. 1950, **6**, 59–63; Apr. **6**, 91–6.—Author discusses briefly the requirements of first-class lubricants in sp. gr., pour points, fl. pt., vis, V.I. etc. He also goes into the description of other lubricating properties incapable of numerical definition. A summary of properties of some inhibitors completes the paper. M. S.

2203. Selenonophosphates as lubricant additives. R. E. Heiks and F. C. Croxton. *Industr. Engng Chem.*, 1951, **43** (4), 876–84.—The preparation and testing of selenonophosphate esters is described. The usual testing procedure for evaluating antoxidants was adopted. The investigations show that the selenonophosphates are satisfactory antoxidants, but their effectiveness depends on the method of preparation and on the base oil in which they are incorporated. W. H.

2204. Patent. Fr.P. 964,501. M. Bestougeff and B. Nikitine. Process for preparation of lubricating oils. 22.1.43, 1.2.50, 17.8.50.

Bitumen, Asphalt, and Tar

2205. Bitumen decomposition with the aid of selective solvents. K. Krenkler *et al.* *Bitumen, Teere, Asphalte, Peche*, 1951, **5** (2), 105–10.—A further decomp of the *n*-heptane high-mol insol was undertaken to ascertain why this does not always correlate with the properties of bitumens of different origin and production. The *n*-heptane insols from the bitumens examined previously (Part II, vol 4/51) were investigated. Mixtures of $\frac{3}{4}$-*n*-heptane and $\frac{1}{4}$-*cyclo*hexane ($\frac{1}{4}$-*cyclo*hexane) and $\frac{1}{4}$-*n*-heptane with $\frac{3}{4}$-*cyclo*hexane ($\frac{3}{4}$-*cyclo*hexane) with solution energies between those of the individual constituents were employed. From the diagrams and curves presented, great diversity exists in the structure of the high-mol asphaltene constituents. Harder steam-dist bitumens contain some $\frac{1}{4}$-*cyclo*hexane insol, whereas cracked residues contain mostly *cyclo*hexane insol. Vac-dist bitumens show an increase in $\frac{1}{4}$-*cyclo*hexane insol, indicating polymerization; the retained plasticity negatives the idea of thermal damage. Differences in the proportions of $\frac{1}{4}$- and $\frac{3}{4}$-*cyclo*hexane insol with increased blowing are shown in bitumens of different origin but similar soft. pt. By the blowing process a slightly plastic material can be converted into a type resembling a normal bitumen and a normal bitumen into a highly plastic material. From the investigation of these material groups it appears possible to penetrate to the true nucleus of bitumens and to explain the different practical behaviour of bitumens of apparently similar quality. R. T.

2206. Effect of synthetic rubbers on properties of petroleum asphalt. H. A. Endres, R. J. Coleman, R. M. Pierson, and E. A. Sinclair. *Industr. Engng Chem.*, 1951, **43** (2), 334–40.—Improvement has been reported of physical properties of asphalt as

a road-surfacing material by addition of synthetic rubbers. Powdered rubbers were added in proportions ranging up to 10% w/w to asphalts and the standard tests carried out on the mixes. Graphs show the effects of the rubbers on soft. pt., penetration, cold flow, etc. Generally it appears that the rubber additives improve the properties required of a road-surfacing material. W. H.

2207. Residues from the distillation of synthetic fatty acids. (Oxide pitches.) E. Gundermann. *Bitumen, Teere, Asphalte, Peche*, 1951, **5** (2), 114–17.—The production of fatty acids and the preparation and properties of oxide pitches are described. In Germany fatty acids are produced preferably from Fischer–Tropsch slack wax with b.p. over 350° C, containing a max of C_{25} to C_{35} paraffins to avoid a low-mol.-wt. product. The oxidized product contains 30 to 35% of mixed fatty acids, also aldehydes, alcohols, dicarboxylic acids, estolides, ketones, ketonic acids, lactones, oxyacids, and unreacted paraffins. The complex mixture of fatty acids produced from this oxidate by conventional methods is vac distilled into 10 to 15% of first runnings, C_4 to C_9 fatty acids, 45% of C_{10} to C_{20} soap fatty acids and 5 to 10% of last runnings. The residue, 7 to 15% of the original fatty acid mixture, resembles tar or pitch, and is termed oxide pitch. Extensive dist does not produce a hard pitch. The oxide pitch reacts with sulphur, forming materials of higher mol. wt. The rise in soft. pt. being dependent on the amount of sulphur, reaction time, and temp. The max reaction temp varies from 190° to 200°. With 10% sulphur chiefly polymerization occurs, with 20% cross-linking with combination of sulphur occurs, and infusible products are formed. The effects of nitric acid are similar to those of blowing, small amounts (5%) of acid sp. gr. 1·385 (about 62% HNO_3) exert a relatively strong polymerizing effect. The sulphur and nitric acid products are gummy and tough but not hard. R. T.

2208. Patents. Austrian P. 165,878. Nostrip, Inc. Bitumen composition to obtain a perfect bond and lasting adhesion to moist stone. 12.6.46, 10.5.50. (Prior. America 1.3.41.)

Fr.P. 964,604. (No patentee given.) Improvement of the adhesiveness of tar and bitumen to stone and the resistivity of bituminous mixtures on compression. 12.4.48, 12.4.50.

Ger.P. 805,764. K. Krenkler and P. Lechler. Emulsions of tar pitch and similar binders. 11.11.49, P 55312D. (31.8.50.) Issued 22.3.51. R. T.

Special Hydrocarbon Products

2209. Insecticides and their study. C. Potter. *J. Roy. Soc. Arts*, 6.4.51, **99** (4844), 388.—A brief account is given of some of the more important synthetic organic chemicals now used as insecticides in plant protection. Various factors are considered which limit the usefulness of existing insecticides and affect the search for new ones, including their human toxicity and the problem of specificity of effects. Lack of knowledge about specificity is proving a severe handicap in the study of the relationship between chemical constitution and insecticidal activity. The effect of insecticides on field populations is discussed; there is need for close study of the general ecological interaction of the insecticide with the population in which it is applied. In this work, and also in work on the problem of resistant strains, a fundamental factor is the specificity of the insecticide used. U. M.

2210. Patent. Fr.P. 957,626–7. A. A. Schaerer. Improvement of the properties of paraffin wax. N. V. De Bataafsche Petroleum Maatschappij. 20.12.47, 22.2.50. (Prior. America 20.12.46.) R. T.

Derived Chemical Products

2211. Butadiene–styrene resinous copolymers. J. D. D'Ianni, L. D. Hess, and W. C. Must. *Industr. Engng Chem.*, 1951, **43** (2), 319–23.—The physical properties of a range of butadiene–styrene copolymers, wt ratios varying from 50/50 to 10/90, are evaluated. Graphs are presented which relate tensile strength, refractive index, heat-distortion point, etc., to the butadiene content. Reference is made to the commercial application of high styrene resins. W. H.

2212. The effect of electrostatic field on the polymerization of styrene. T. Titani and G. Mesituka. *Bull. Chem. Soc. Japan*, Dec. 1950, **23** (6), 212.—The bond strengths and nature of the bonds in the polystyrene molecule are described and discussed. From the conclusions drawn, it is indicated that as a result of polarization during polymerization the end of the chain molecule must be positively polarized while the body of the molecule is negatively polarized. When a certain degree of polarization is reached the positively polarized end must be pulled into the negatively polarized clew-formed body of the molecule, and thus the growth of the molecular chain is stopped. Experiments are described, which were made to ascertain whether the application of an electrostatic field would pull out the positively polarized end and allow further polymerization to take place, proved the above point. Polystyrene prepared by heating liquid styrene at 120° C for 3 to 4 hr under the influence of an electrostatic field of 800 to 9000 V/cm had a mol. wt. 35 to 36% higher than that of polystyrene formed under the same conditions but without an electric field. The results showed that not only the degree of polymerization, but also the quantities of polymerization somewhat increased under the influence of the electrostatic field.

W. H. C.

2213. The increase of the mean molecular weight of polystyrene under the influence of the electrostatic field. G. Mesituka. *Bull. Chem. Soc. Japan*, Dec. 1950, **23** (6), 214.—In an earlier paper (*see* Abs. No. 2212) it was shown that the rate of increase in the degree of polymerization is much larger than that in the quantities of polymerization. This result suggested that not only the rate of chain growth, viz., the rate of addition of the monomer molecule to the polymer molecule, but also the rate of coupling, viz., the rate of combination of the polymer molecules with each other, must increase under the influence of an electrostatic field. With this in view an electrostatic field was applied to a benzene solution of the already polymerized polystyrene, and it was found that the mean mol. wt. of the polystyrene was remarkably increased. Starting with polystyrene of mean mol. wt. of 148,000 and an applied voltage of 500, 1000, 2000, 4000, and 8000 V/cm, at 60° C, for 50 hr, the mean mol. wt. of the product was found to be : 150,000, 160,000, 164,000, 169,000, and 240,000, respectively. The viscosity of the corresponding solutions was found to remain constant notwithstanding the increasing mol. wt. of the polymer. An explanation of this is given. W. H. C.

Coal, Shale, and Peat

2214. Modern theory on the structure and caking properties of coal from the rheological standpoint. K. Inouye. *J. Coll. Sci.*, 1951, **6**, 190–210.—It is supposed that the caking properties of coal are caused by weaknesses of the intermolecular forces, which can be evaluated by means of Young's modulus (M). M of 120 coals from lignite to anthracite has been measured by a resonant frequency method and correlated with the % volatile matter on a dry, ash-free basis. The influence of orientation of specimen and moisture on M are discussed.

If coal be considered in its simplest division as mixtures of "bitumen" and "residue," correlation of "bitumen" content B with M leads to the idea that the "bitumen" molecules with weak intermolecular forces act as a kind of plasticizer agent to weaken the total forces and so determine the caking properties. It is found experimentally that $M = M_0(1 + 7500K/B^2)$, where M_0 = Young's modulus of a "pure" (ash-free) coal and K is a constant. The essential conditions for caking properties are small M_0 and large K; *i.e.*, the intermolecular forces of the coal must be weak and the molecules must sorbate as strongly as possible around the ash particles.

Different grades of coal are represented on the basis of this idea by a series of models. H. C. E.

2215. Characteristics and utilization of oil-shale and shale oil. H. M. Thorne, W. I. R. Murphy, J. S. Ball, K. E. Stanfield, and J. W. Horne. *Industr. Engng Chem.*, 1951, **43** (1), 20–7.—A more detailed discussion of the research and process development work in progress at the Laramie, Wyo., station of the Bureau of Mines (*see* Abs. No. 2219). The properties of Green River oil shale are compared with those of other oil shales, and the properties of the products obtained by retorting oil shale and refining the products are evaluated for several processes. F. M.

2216. Heat requirements for retorting oil shale. H. W. Sohns, L. E. Mitchell, R. J. Cox, W. I. Barnet, and W. I. R. Murphy. *Industr. Engng Chem.*, 1951, **43** (1), 33–6.—The overall heat requirements for retorting Colorado oil shales, of 28 gal/ton and 57 gal/ton, have been determined for various temp above 77° F in an experimental retort. Details of the equipment used are given, and experimental results are tabulated together with graphical presentation of the heat content (B.Th.U/lb) of the two shales and spent shale against temp. F. M.

2217. Liquid fuels from oil shale. W. G. Hull, B. Guthrie, and E. M. Sipprelle. *Industr. Engng Chem.*, 1951, **43** (1), 2–15.—A staff–industry collaborative report on the mining and retorting of oil shale and the refining of shale oil at the U.S. Bureau of Mines oil-shale demonstration plant at Rifle, Colorado. Methods of mining and direct mining costs are discussed and the forward mining research programme outlined. Crushing and retorting are described in detail with flow diagrams and the gas-flow retorting process, the NTU retort, the Union Oil Co. of California retort, and the Standard Oil Dev. Co. fluid process. Tabular and graphical summaries are given of operating data of gas-combustion retorting for constant shale grade with variable gas–air ratio and variable inlet-gas velocity. A brief account is given of the refining processes with details of the materials of construction used throughout. F. M.

2218. Oil-shale research and process development. K. E. Stanfield and H. M. Thorne. *Industr. Engng Chem.*, 1951, **43** (1), 16–19.—A description of the Petroleum and Oil-shale Experimental Station of the U.S. Bureau of Mines at Laramie, Wyo., with a brief account of the research programmes on petroleum production, petroleum chemistry and refining, oil-shale analysis, retorting, refining, and oil-shale and shale-oil by-products. F. M.

2219. Shale-oil refining. J. D. Lankford and C. F. Ellis. *Industr. Engng Chem.*, 1951, **43** (1), 27–32.—Details are given of a 100 to 200 b.d. distillation-cracking plant designed to study the yields and product quality obtained by refining shale oil from Californian oil shale at the U.S. Bureau of Mines Station at Rifle, Colo. Summaries of distillation, vis-breaking, recycle cracking, and coking operations are given with tabulated data on the quality of finished naphtha and diesel oil. Details of the treatment required to produce products meeting current market specification are given. F. M.

Corrosion

2220. Aluminium marine pipeline. E. T. Wanderer. *Oil Gas J.*, 5.7.51, **50** (9), 58.—An experimental aluminium pipeline built to resist corrosion in seawater has been laid in the Gulf of Mexico. It is part of offshore pipeline system supplying gas to Aluminium Co. of America at Port Lavaca, Texas, and is about 3500 ft in length, welded in 400-ft sections on shore. Welded joints were coated and wrapped, and the 400-ft sections launched from pontoons. Results show that offshore aluminium lines are practical and have an economic advantage over steel. Tables give composition and properties of aluminium alloy. G. A. C.

2221. Application of clad steels in the petroleum industry. J. Erskine. *Brit. Petrol. Equip. News*, 1951, **2** (1), 27.—A description is given of the process of manufacturing clad steels developed by Colvilles Ltd., and annotated drawings of the sections of the mild-steel slabs and the corrosion-resistant materials assembled for bonding by hot rolling are also given. Clad plates are hot rolled in pairs from the conventional composite slab illustrated. This comprises two mild-steel slabs between which are inserted a pair of relatively thin stainless-steel plates, the latter having a refractory powder between them to prevent sticking. With chromium alloy steels a sub-microscopic film of chromium oxide forms which creates a barrier of free diffusion and prevents proper bonding. This is overcome by arc depositing $\frac{1}{4}$ inch of mild steel on the surface of the chromium steel slab of 6 inches thickness. Bonding is accomplished in the subsequent hot rolling of the slab to the thickness required, which is usually $\frac{1}{4}$ inch. Specifications are tabulated for four " Colclad " alloys in which the austenitic

stainless steels are stabilized with either columbium or titanium. Low- and high-power photomicrographs of the bond between mild steel and 18/8 stainless steel are shown. The mechanical properties of clad plates and efficiencies of the bond are described. The hot forming, gas cutting, and welding of clad plates are described and illustrated. W. H. C.

2222. Corrosion and its control. M. E. Parker. *Oil Gas J.*, 21.6.51, **50** (7), 338.—Pt 16 in this series deals with the installation and use of test leads on pipelines.

Locations calling for test leads include road crossings, pipeline crossings, junctions, rectifier installations, and electric-rail crossings.

There is no need for very elaborate installations. G. A. C.

2223. Corrosion and its control. M. E. Parker. *Oil Gas J.*, 28.6.51, **50** (8), 94.—Pt 17 of the series deals with measurement of electrical constants of a pipeline, in particular the determination of characteristic resistance across an interruption in the pipe and where no break exists in the line. An example is worked out. G. A. C.

2224. Corrosion and its control. M. E. Parker. *Oil Gas J.*, 5.7.51, **50** (9), 81.—Pt 18 of this series deals with insulated joints in cathodic protection. Such joints isolate the structure from others, and also separate a group into units for protection.

Isolation is most important, so that current is not drained off to other structures such as tank bottoms and disused pipes.

Daily checks of voltage across insulated joints should be carried out. G. A. C.

2225. Corrosion resistance of anodized and unanodized titanium. Chuk-Ching Ma and E. M. Peres. *Industr. Engng Chem.*, 1951, **43** (3), 657–9.—The corrosion resistance of anodized and unanodized titanium towards the common mineral acids is reported. Alternate and total-immersion tests were employed to obtain rates of corrosion of Ti in various concentrations of HNO_3, HCl, and H_2SO_4 as well as their mixtures. E. J. C.

Engines and Automotive Equipment

2226. Diesel electric tractor. Anon. *Gas Oil Pwr*, 1951, **46**, 142–4.—Designed by Letourneau Inc., this machine embodies diesel-electric drive to rubber-tyred wheels, and is used for handling earth-moving equipment. The power unit is a G.M. two-stroke six-cylinder engine of bore and stroke 4¼ inches and 5 inches respectively, and provides a max of 186 b.h.p. at 1800 r.p.m. to two generators mounted in line with the engine.

The D.C. generator supplies power to each of the four drive wheels; the A.C. generator supplies power to steering motors for front and rear wheels and to a motor-operated winch at the rear. Since all the motors are placed at the points of application of power, intermediate drives and gears are eliminated. All operations are controlled from a single panel.

It is claimed that the unit can start smoothly, pull smoothly, and stop quickly. Power is supplied potentiometrically to the drive motors, and the absence of all mechanical connexions reduces the power loss to a minimum. On gradients the load's tendency to overspeed the motors acts as an automatic brake. H. C. E.

2227. Improvements to the Kromhout A190 engine. Anon. *Gas Oil Pwr*, 1951, **46**, 119–22.—Discusses improvements and modifications to an engine previously described (Abs. No. 1234, 1949).

The individual fuel pumps have been replaced by two Bosch multiple fuel pumps. Because the piston heads tended to crack, the pistons are now oil-cooled through hollow connecting-rods. The fuel-pump arrangements have been improved in order to simplify reverse running. H. C. E.

2228. Main line locomotive power unit. Anon. *Gas Oil Pwr*, 1951, **46**, 137–9, 146.—The Ruston–Paxman YL engine is made in units of eight, twelve, or sixteen cylinders in Vee form, covering a power range from 384 to 2470 b.h.p. The cylinders are of 9¾-inch bore and 10½-inch stroke.

The twelve-cylinder unit operates at 750 or 1000 r.p.m. on continuous or maximum load, and is designed for normal aspiration or for medium- or high-pressure turbo-charging. The Al alloy pistons carry three compression and two scraper rings. On high-pressure-charged engines the pistons are cooled with oil supplied through the drilled connecting-rods. The cylinder-heads carry two exhaust and two inlet valves with separate inlet ports. Dilution of lub oil by fuel is avoided by providing a separate system for the fuel-pump camshafts.

Details of the engine construction, and of the B.T.H. generator unit, are given.

H. C. E.

2229. Ruston YE class [diesel] engines. Anon. *Gas Oil Pwr*, 1951, **46**, 113, 123.—These engines, for heavy duty work, are constructed in units of four, five, or six cylinders, the dimensions of which are 5 inches by 5½ inches. The piston speed is 1470 f.p.m. at 1500 r.p.m. The continuous ratings of the three units are 75, 94, and 112 b.h.p. respectively at 1500 r.p.m., but in special circumstances the output can be increased to 90, 112·5, and 135 b.h.p. respectively for short periods at 1800 r.p.m.

Lub oil is delivered under pressure from the sump to all working parts of the engine, and the construction is such that the pump is submerged even when the engine is operating on grades of 1 in 4.

The pistons of silicon-aluminium alloy have three pressure and two scraper rings. The combustion chamber is formed in the top of the piston. Construction and accessories of the engine are briefly described. (See also Abs. No. 1547.)

H. C. E.

2230. Small enclosed horizontal [diesel engine]. Anon. *Gas Oil Pwr*, 1951, **46**, 152.—This National AHI direct-injection unit has a single cylinder of dimensions 3·15 inches bore and 4·33 inches stroke. It operates on gas or fuel oil, giving a power output of 3, 4, 5, or 6 b.h.p. at 1000, 1200, 1500, or 1800 r.p.m. respectively.

Three chromium-plated compression rings and one scraper ring are fitted, and the piston crown contains a bowl-shaped combustion chamber. Pressure lubrication is supplied to big-end bearings and valve gear; the piston and small-end bearing are splash-lubricated.

If required to run on gas the fuel pump and injector are replaced by a mixing valve and magneto. The C.R. of 16·5 : 1 remains the same. In working order the unit weighs 524 lb.

H. C. E.

2231. Production diesel car. Anon. *Gas Oil Pwr*, 1951, **46**, 146.—Reviews the outlook for oil engines in private motor cars and describes the performance of a Mercedes-Benz four-cylinder unit developing 38 b.h.p. The weight of this car is *ca* 130 lb greater than that of a petrol-driven model, and its cost (in Switzerland) is *ca* £200 higher.

H. C. E.

2232. First International I.C. Engine Congress. Anon. *Gas Oil Pwr*, 1951, **46**, 108–12, 118, 147–8.—A summary of the papers and discussion at the Congress held in Paris May 7–19, 1951. Abstracts are given of the papers, of which the following are of interest: Investigations to obtain a maximum thermal efficiency with diesel engines, E. Sörensen and K. Zinner; Supercharging of internal combustion engines, H. R. Ricardo; Present position of double-acting engines, de Pieri; Design and operation of exhaust-driven turbo-compressors for diesel engines, A. J. Penn; Water and oil coolers for internal combustion engines, M. Rabilloud; Offset turbulent combusion chamber, J. H. Bradbury; Research into exhaust manifolds, P. H. Schweitzer; Automobile diesel engine, M. Moreau; Investigations into the cause of crankshaft corrosion, W. J. Muller; Filtering of diesel fuel, — Heinrich; Crankcase explosions, D. J. Hoare and A. M. Conybear; Rail traction diesel engine, J. M. Smith.

Reports of detailed discussions on some of the papers are given.

H. C. E.

2233. Machinery for high-powered ships. H. Andresen. *Motor Ship*, July 1951, **32** (376), 142.—This extract from a paper, read before the Congrès Internationale des Moteurs in Paris, makes a survey of the various possibilities of increasing the competitive power of modern marine diesel plant. This can be done by increasing the output, improving economy, making reductions in weight and space requirements,

and improving the maintenance characteristics. Mention is made of the use of boiler oil, and the importance of the choice of engine types and shaft arrangements is discussed. U. M.

2234. Progress in marine engineering. T. A. Crowe. *Motor Ship*, July 1951, **32** (376), 148.—Extracts are given of part of a paper read at the Joint Engineering Conference, 1951. An attempt is made to forecast future developments in steam machinery, gas turbines, and diesel engines, and the possibility of the use of nuclear energy for ship propulsion is considered. Six literature references are given. U. M.

2235. Some research and development work on large marine engines. P. Jackson. *Motor Ship*, June 1951, **32** (375), 100.—Tests on the use of fuel oils of 3500 sec visc, using a 1100-b.h.p. single-cylinder engine of 670 mm bore and a four-cylinder engine of 600 mm bore, are described. From the results obtained it is considered that large marine engines of Doxford type can operate at sea on such fuels, and recommendations are given for correct treating of the fuel.

A particular case of crankcase corrosion, caused by contamination of coolant by seawater and subsequent leakage of coolant into crankcase, led to development of an inhibitor for cooling water. Experiments showed that the addition of sodium nitrite to the normal Doxford cooling water containing potassium dichromate gave a solution which attacked neither the ferrous nor the tinned copper parts even when contaminated by 25% of seawater. In the event of this contaminated coolant entering the crankcase, lubrication continues and bearing surfaces are not attacked. Similar results were obtained by addition of a soluble oil to cooling water, most satisfactory oil being Dromus "D," in proportion of 5 gal to 1000 gal of water.

The results of a great deal of work carried out to investigate problem of crankcase explosions, and all possible safeguards against such disasters, are summarized. In view of tests carried out, crankcases of Doxford engine seem safe from possibility of explosion. U. M.

Safety Precautions

2236. I.P. Safety Codes—application to drilling and production. H. de Wilde. *J. Inst. Petrol.*, 1951, **37**, 181–5. A. R. W. B.

2237. I.P. Safety Codes—application to refining. F. Mayo. *J. Inst. Petrol.*, 1951, **37**, 186–92.—Relevant literature on this subject is mentioned, and the scope of the code is indicated and discussed. A. R. W. B.

2238. I.P. Safety Codes—application to marketing. R. L. Sarjeant. *J. Inst. Petrol.*, 1951, **37**, 192–7.—The scope of the proposed code is indicated, and a brief discussion of the chapters already drafted is given. A. R. W. B.

2239. Make safety a habit. Anon. *Oil Gas J.*, 28.6.51, **50** (8), 68.—A special safety programme instituted by the Standard Oil Co. (Ohio) has reduced accidents from 12·87 per million man hr in 1946 to 4·60 in 1950, a reduction of over 65%. Promotional and educational efforts combined with supply of items of personal protection such as gas masks, hose masks, respirators, goggles, gas detectors, etc., have contributed to the good results.

Alarms have been installed in the gas-compressor house, and all tank cleaning is carried out strictly according to API recommendations. G. A. C.

2240. Model code of safe practice in the petroleum industry. E. J. Sturgess. *J. Inst. Petrol.*, 1951, **37**, 163–9.—The results are described of tests carried out to determine the extent of an explosive atmosphere around storage tanks, etc., during the normal operations of a marketing installation. The "Poole" explosimeter was used in most cases for testing, and a clear relationship was demonstrated between the volume of vapour discharged and the distance over which an explosive mixture is found. A. R. W. B.

MISCELLANEOUS

2241. Digest of technical proceedings. Third World Petroleum Congress. Anon. *Oil Gas J.*, 31.5.51, **50** (4), 95.—The first of two technical reports covering engineering papers at the Hague Congress is given in two sections, Geology and Geophysics, and Drilling and Production.

Fifty-one papers are abstracted. G. A. C.

2242. Europe's position in world's petroleum industry. B. Fleszar. *Nafta*, Jan.–Feb. 1950, **6**, 32–8; Mar. 1950, **6**, 67–71.—Author gives a map of European oilfields and production during the years 1939–49. U.S.S.R., Great Britain, France, and Germany are treated in greater detail. M. S.

2243. Future fuel and lubricant research station of the Institut français du Pétrole. Anon. *Rev. Inst. franç. Pétrole*, 1951, **5**, 156–63.—A description (with plan) of the proposed establishment. Particular attention will be paid to engine tests on lub oils; principal features of CRC lub oil tests are tabulated, equipment for carrying out the L1, L4, L5, 1D, and FL2 tests will be installed, also facilities for testing hypoid axles according to L20 and L21. V. B.

2244. Organization and work of the French Institute of Petroleum. E. A. Smith. *I.P. Review*, 1951, **5**, 65.—The general petroleum situation in France is different from that in the U.K., because, although France consumes about 13,000,000 metric tons of oil a year, she does not have the advantage of the laboratories attached to major oil companies. Hence one of the main functions of the French Institute of Petroleum is to look after the development of the production and utilization of oil. Therefore, although it holds meetings and issues technical publications in the same way as its British counterpart, there the likeness ends. It is, in addition, a centre of research financed by the French petroleum industry covering all aspects of petroleum and having two specialized high schools, one of university status. Details are given of research carried out, which includes work on fuels and lubricants, oilfield research, geological investigations, applied physics, fundamental chemistry, and analytical chemistry. R. H.

2245. Petrochemicals in the southwest. G. Weber. *Oil Gas J.*, 3.5.51, **49** (52), 112.—A review of the petrochemical industry is given. Forty-three companies now produce or process petrochemicals in fifty-one plants in the southwest (U.S.A.); seventeen of them are in petroleum refineries.

Figures shown include production and value of major olefins consumed by the petrochemical industry 1940–50, commercial uses of petrochemicals, chemicals from ethylene, synthetic ammonia, and nitrogeneous fertilizer production; and the figures are discussed.

Petrochemical plants and principal products are tabulated. G. A. C.

2246. The Second Baku. H. Hassmann. *Erdöl u. Kohle*, 1951, **4**, 290–3.—Second Baku is region in east of European U.S.S.R. approx size of Spain and lying between Volga and Urals. Four main areas are centred on Molotov, Ufa, Kuibishev, and Saratov, the first three being oil and the latter gas. Production of region has increased from 600 tons/year (1929) to 10·6 million (1950), latter is 28% of U.S.S.R. output. Details are given of administration, fields, refineries, and pipelines in each of above four areas. Known refining capacity of the region is over 5 million tons/year. V. B.

2247. 75 years' history of the American Chemical Society. *Industr. Engng Chem.*, 1951, **43** (2), 264–311; 809–19.—Papers are presented by a number of authors on the progress of various branches of chemical science during the past seventy-five years, and the part the American Chemical Society has played is considered. The history of petroleum chemistry is traced back to 1859. W. H.

2248. A fractionating column to provide water of various dissolved oxygen content. F. E. J. Fry. *Canad. J. Tech.*, 1951, **29**, 144.—A train described through which water is cascaded downward while nitrogen passes upwards slowly. Water is drawn off at different levels, and oxygen content is progressively decreased. The range of oxygen content found in a typical run varies from 4·84 ml/litre to 0·34 ml/litre, sixty steps existing between these two levels. A. D.

2249. Diffused air floats particles for waste disposal. A. I. Barry. *Chem. Engng*, 1951, **58** (4), 107–10.—Purification before disposal of waste water is effected by a froth-flotation process in paper-mills, oil refineries, and other industries. Capacities are 3 to 6 g.p.m/sq. ft. of tank surface. The process is by flocculating chemically and agitating with a stream of water containing minute air bubbles less than 0·001 inch in dia. These are formed by drawing in 10 to 40 cc air per gal and passing through a high-velocity centrifugal pump. The effluent–air mixture rises in the centre compartment of the flotation tank, and froth is skimmed off. Clarified water discharges near the bottom of the tank. 98% removal of paper fibre was achieved from a waste containing 193 p.p.m. of suspended solids. D. H.

2250. Export packing of petroleum and engineering equipment. J. E. E. Cook. *Brit. Petrol. Equip. News*, 1951, **2** (1), 43.—A review is given of the conditions of shipment and methods of packing since pre-war days. It is emphasized that packaging is given too little managerial attention, although it absorbs about 10% of the selling price of the product. It is the opinion of many in the Institute of Packing that the question should be taken out of the hands of the packing foreman or export manager and placed on the directors' agenda—and kept there. The many aspects of packing are described, and the principles of protection from atmospheric humidity, corrosive factory atmospheres, dust, and casual finger-prints (which are extremely corrosive), and exposure to physical or mechanical damage through carelessness or accident, are discussed with respect to factory layout, etc. The principle should be to get the products protected and into dry clean storage as quickly as possible. Some protective measures can be commenced during production itself. Rust-inhibitive coolants and process oils, and precautions when dealing with precision surfaces are discussed. The preparation and packing of heavy machinery, etc., is outlined under the following sections: long and heavy items such as axles, precision shafting, etc., large and brittle items, machinery generally, overhanging members, protruding members, giant machines, tools and spares going with machinery, internal-combustion engines, etc. Ten commandments which should never be broken are listed. The adoption of skid-type internally battened construction is recommended for any case too heavy to man-handle. W. H. C.

2251. Foreign trade of the Federal (German) Republic in minerals oils, mineral oil products, coal by-products in 1950. F. Below. *Bitumen, Teere, Asphalte, Peche*, 1951, **5** (2), 111–13.—During 1950 the Federal Republic, for the first time since the war, made considerable progress in foreign trade. Reciprocal trade was carried on with practically all western and some eastern countries. Imports exceeded, but exports were still below the pre-war figures. A comparative analysis of the relevant import and export data is tabulated. Further, a detailed account of the trade in special products of the coal and oil industries as regards quantities, values, customers, and suppliers is presented. R. T.

2252. LPG sales continue to gain. K. W. Rugh and G. R. Berg. *Refiner*, 1951, **30** (1), 69–70.—A short review of the marketing and demand of LPG in the U.S.A. Sales of LPG in 1950 reached an estimated 3,333,000,000 gal (U.S.) exclusive of any used in the manufacture of aviation and motor fuel and synthetic rubber. This is an increase of 25·4% over 1949, and is more than three times the vol sold in 1945. The greatest demand, 2,143,000,000 gal, was for domestic purposes. Chemical manufacture took 650,000,000 gal, and synthetic rubber preparation 207,000,000 gal. A demand is also being created by its use in automotive engines. Buses are now being built, with a C.R. as high as 12 : 1. It is envisaged that the demand for LPG will increase in the immediate future. Reserves of LPG are estimated at 80% of gasoline in the total petroleum reserves. R. W. G.

2253. Materials adsorbed at crude petroleum–water interfaces. M. O. Denekas, F. T. Carlson, J. W. Moore, and C. G. Dodd. *Industr. Engng Chem.*, 1951, **43** (5), 1165–9.—The water-spray extraction method of Bartell and Niederhauser was employed to isolate film-forming and surface-active constituents from crude petroleum. One fraction of the extract was shown to consist of *n*-paraffins containing up to seventy or eighty carbon atoms. This suggested that high-molecular-weight *n*-paraffins might be obtained from crude petroleum more readily by extraction than by chemical synthesis.

A further suggestion was that wax-containing films deposited on rock surfaces might influence core analysis procedures, laboratory flooding tests, and recovery of petroleum from depleted reservoirs by air and water drive. E. J. C.

2254. Memorandum on the unit of heat. Sir Charles Darwin. *J. Inst. Petrol.*, 1951, **37**, 158.—This memorandum recently circulated by the Royal Society is reproduced, and it is requested that comments on its applicablity to the petroleum industry should be sent to the Institute of Petroleum. A. R. W. B.

2255. Refinery operations to continue at record levels. Anon. *Refiner*, 1951, **30** (3), 71–5.—An extensive review of the U.S. petroleum figures for the last ten years and U.S. crude consumption since 1918. The 1950 average crude runs to stills reached an all-time peak of 5,735,000 b.d. with a refining capacity of 6,724,000 b.d. by the end of the year. 1951 demand figures expected to show a further increase due to high domestic demand.

Over the last ten years (1941–50) gasoline production has increased by 34·5% (% on crude down from 45·7 to 42·3), kerosine by 62·8 (% on crude up from 5·3 to 5·7), distillate fuel oil by 110·2% (% on crude up from 13·7 to 21·3), residual fuel oils by 13·8% (% on crude down from 24·9 to 20·9), and lubricating oil by 30·1% (% on crude down from 2·8 to 2·6). R. W. G.

2256. A new development in radiant heating for the petroleum industry. C. C. Tate. *Oil Gas J.*, 10.5.51, **50** (1), 106.—The radiant-heat source is a high-efficiency heater which is easily installed, has low maintenance and fuel costs, and gives smooth operation with high wind velocities and is flexible in control.

The radiant section is 38 ft 6 inches in length, 5 ft in width, and 12 ft high; the convection section is of same length, but is 2 ft 3 inches wide and 6 ft 1¼ inches high.

Convection tubes are in equilateral spacing. Fifty-six ceramic burners are mounted in each wall, each burner is independently controlled. G. A. C.

BOOK REVIEWS

Possible Future Petroleum Provinces of North America. A Symposium edited by M. W. Ball, A. A. Baker, G. V. Cohee, P. B. Whitney, and D. Ball. Tulsa, U.S.A.: American Association of Petroleum Geologists, 1951. Pp. 358. $4.*

This book is the February 1951 number of the *Bulletin of the American Association of Petroleum Geologists* (Vol. 35, No. 2) published in book form, but its importance is so great that the Association has done a useful service in publishing it as a self-contained volume.

In 1941 a similar stocktaking of the oil possibilities of North America was undertaken by an A.A.P.G. committee, and it is interesting to observe how the outlook has grown, both geographically and geologically, in the interval. The 1941 volume, as Max Ball points out in his Foreword, contained no mention of the Continental Shelf and no suggestion of the importance of reefs; it gave little consideration to possibilities in deeper strata in geological basins already productive in upper beds; and it considered no possibilities deeper than 15,000 ft. Since then geological conceptions have both widened and deepened in pace with, or a little ahead of, the advance in physical techniques. Speculative thinking calls for new techniques, and consequent developments stimulate still further speculation—and so we go jerkily onward. And yet, notwithstanding the cumulative experience of so many years of intensive research,

* To members $2.50.

the tempo of oil-finding in the U.S. is decreasing, and the decade since 1941 has not seen the discovery of as much new oil as either of the two previous ones. There is no question that most of the easy sitters have been found, drilling on seepages and surface anticlines in the U.S. belongs to a past, though very prolific, phase; the oil of to-morrow will require more refined methods, both geological and geophysical for its discovery, and the most important ingredient is speculative geological thinking.

One of the most important results of the 1941 stocktaking was the emphasis placed on the prospects of Western Canada. Up till then Western Canada had only yielded two important fields, Turner Valley in Alberta and Norman Wells in the remote northwest. Scores of wildcats had been drilled in the foot-hills and plains, but only some minor fields, mostly of heavy oil, had been revealed. Yet a critical study of all the circumstances had then indicated that, notwithstanding these discouraging results, there was good reason to place a high value on the prospects of the zone as a whole—a prediction which has been abundantly justified by subsequent events.

The 1951 volume has already, since its preparation, been justified in one prediction—namely on the prospective value of the Williston Basin of North Dakota. An important discovery in this basin some months ago has transformed North Dakota to oil-boom activity.

In most of the states examined in this volume the predictions of future discovery depend on intensive in-fill exploration between proved fields rather than on brand-new prospects. The evidence from important wildcats is carefully reviewed, and all the conditions, stratigraphical and structural, are analysed in all their aspects. Stratigraphic trap exploration only becomes possible when a sufficient control from drilled wells allows the search to be reasonably localized. Reef exploration is particularly hazardous until some guidance emerges on trends or unless the conditions permit of geophysical help—which is not always the case.

The oil possibilities of continental shelves have received much, perhaps overmuch, advertisement in literature in recent years. In this volume the prospects of the sectors of the maritime states are discussed as part of each state in some cases, in others they are not even mentioned. The shelf areas of Southern California and of Texas and Louisiana are naturally assigned a high prospective value in that they are adjacent to or already contain oilfields, but elsewhere no firm opinions are expressed. The shelf area of Alaska is attractive in its extent, but as the prospects on land have so far proved so fickle it follows that the adjacent sea area cannot be valued too highly at present. The Atlantic continental shelf is mostly discounted, though in some sectors with qualifying reservations. G. M. L.

Hilfsbuch für Mineralöltechniker. 1. Bd. Die Eigenschaften von Kohlenwasserstoffen, Mineralölprodukten und Hilfsstoffen. A. F. Orlicek and H. Pöll. Vienna: Springer-Verlag, 1951. Pp. viii + 173 + 134 charts. £4 12*s*. 6*d*.

The authors state that this book has been written for the benefit of various groups of technologists in the German petroleum industry such as plant designers, engineers, chemists and works management with the object of presenting in a concise form the physical constants and methods of calculation which are relevant to petroleum technology. It is pointed out that there is a lack of such a reference book in German and that when data are obtained from English or American literature, conversion of the units to the metric system is necessary.

The present volume deals with the physical properties of hydrocarbons, petroleum products, and refinery chemicals, while a second volume will be concerned with the fundamentals of refining operations. The scope of the first volume can be judged from the chapter headings: Introduction to the chemistry of hydrocarbons and the characterization of crude oil and its products; Density and specific gravity; Equations of state for gases and vapours; Viscosity; Vapour pressure; Specific heats; Heats of vaporization, of fusion, of solution, and of mixing; and Enthalpy and entropy. Other chapters are concerned with the thermal conductivity of metals and of insulating materials, and with vapour/liquid and liquid/liquid equilibria. The format of the earlier chapters is the same and covers the definition of the physical property, the metric units of measurement, conversion factors for

the various English or American units, and equations for determining the effect of temperature or pressure on the physical property.

Certain information, on density, boiling point, melting point, latent heats, critical constants, aniline point, and octane number is presented in tabular form, while all graphical data are collected in 134 graphs at the back of the book. These figures give information such as the specific volume, compressibility, viscosity, vapour pressure, specific heat, enthalpy, and equilibrium vaporization constants for individual hydrocarbons.

The information given in this first volume is extensive and has been presented well in a clear and systematic manner. Although no index is appended to this volume (a combined index for the two volumes will appear in the second volume), the systematic subdivision of the subject matter helped in locating specific inquiries. Nevertheless, in a book of this nature, an index to each volume would be appreciated. From the user's viewpoint this book has the merit of many (47) fully worked examples of calculations which are interspersed in the text to illustrate the application of equations, conversion factors, and nomograms. In addition to clarifying the text, these examples are useful for giving a common basis of calculation for different workers in one organization. In this way numerical differences due to the use of various sources of data and diverse methods of calculations can be eliminated. It is important in a book of this type that references to the original literature should be extensive, and the bibliography of this book is generally good.

The book bears many resemblances in scope, format, and illustration by examples to J. B. Maxwell's recent book, "Data Book on Hydrocarbons." Drs Orlicek and Pöll's book has, however, additional information on refinery chemicals and other organic compounds. This book will be of considerable use to the German petroleum technologist. The English or American reader will find it useful if he is prepared to face the conversion of data from metric to f.p.s. units. J. A. E. M.

Creep of Metals. L. A. Rotherham. London: Institute of Physics, 1951. Pp. 80. 15*s*.

This monograph marks a new departure in the "Physics in Industry" series of the Institute of Physics, in that hitherto lectures and symposia arranged by the Institute have been published only in the series.

The author of the present work is to be thanked for dealing exhaustively but at the same time clearly and concisely with a subject which has been the object of much investigation and debate. His book, taking the general creep curve as a model, proceeds to discuss its component parts and the fundamental principles operative in giving each part its characteristic shape. This treatment naturally calls for some mathematical reasoning, but the purely mathematical side has been reduced to a minimum. The crystallographic data given are clearly explained in their application, as is the dislocation hypothesis, but, while the author has compiled a reference volume of great value to anyone acquainted with the subject, it might prove difficult reading for the person casually interested. On the other hand, as an introduction to a serious study of the subject, it would be difficult to find a more valuable book. Furthermore, the style and quality of reproduction are of a high order. R. G.

ADDITIONS TO LIBRARY

British Standards. London: British Standards Institution.

B.S. 1740: 1951. Wrought pipe fittings iron and steel (screwed B.S.P. thread). Pp. 38. 5*s*. post free.

B.S. 1782: 1951. Hose couplings (1½-inch to 8-inch nominal sizes) other than fire-hose couplings.

Symposium on Methods of Measuring Viscosity at High Rates of Shear. Philadelphia, Pa.: American Society for Testing Materials, 1951. Pp. 48. $1.35.

The purpose of this symposium was to find a suitable method for testing viscosity at high rates of shear of various additives used in lubricants and fluids. Existing methods proved unsatisfactory due to unknown temperature values; therefore two promising methods were investigated. The results—described in detail in this report—were presented to the API Committee on Petroleum Products in 1949 and to the Research Division VII on Flow Properties, ASTM Committee D-2 on Petroleum Products and Lubricants in 1950.

The published symposium includes an introduction by J. C. Geniesse, and "Viscosity–shear behaviour of two non-Newtonian polymer-blended oils," M. R. Fenske, E. E. Klaus, and R. W. Dannenbrink; "The Kingsbury tapered-plug viscometer for determining viscosity variations with temperature and rate of shear," S. J. Needs; and "The comparison of viscosity–shear data obtained with the Kingsbury tapered-plug viscometer and the PRL high shear capillary viscometer," discussion by Messrs Fenske, Klaus, and Dannenbrink.

APPLICATIONS FOR MEMBERSHIP OR TRANSFER

SEPTEMBER 1951

The following have applied for admission to or transfer of membership in the Institute. In accordance with the By-laws, the proposals will not be considered until the lapse of at least one month after the publication of this *Journal*, during which time any Fellow, Member, Associate Fellow, or Associate Member may communicate by letter to the Secretary, for the confidential information of the Council, any particulars he may possess respecting the qualifications or suitability of the candidate.

The object of this information is to assist the Council in grading the candidate according to the class of membership.

The name of candidates' proposers and seconders are given in parentheses.

Application for Membership

ANDERS, Ostman Carl, engineer, Svenska Petroleum Aktiebolaget Standard. (*G. Karlbom; K. E. Swendsen.*)

ARCHER, Michael, technical assistant, Anglo-Iranian Oil Co. Ltd. (*P. Docksey; D. Commins.*)

BANERJEE, Dhirendra Mohan, senior scientific assistant, T.D.E.S. Laboratories. (*B. S. Duegan; E. Venkatachalam.*)

BASHOURAN, Ahmad, Chemical & Development Section, Anglo-Iranian Oil Co. Ltd. (*M. H. Farmer; R. Sumer.*)

BERGIN, Bertram Roy, Squadron Leader, Royal Air Force. (*E. H. Jenkins; L. H. Cooper.*)

BILTON, Donald Percival, sales director, Vigzol Oil Co. Ltd. (*S. Elliman; A. E. Hope.*)

BLIGHT, Richard Delaney Hathway, engineer representative, Messrs. C. C. Wakefield & Co. Ltd. (*G. Reid; R. H. Vernon.*)

BOWEN, Idris Gwynne, senior gas turbine technician, Shell Petroleum Co. Ltd. (*W. S. Ault; D. L. Samuel.*)

BURTON, Stanley Witterick George, assistant accountant, Kuwait Oil Co. Ltd. (*R. M. S. Owen; J. D. Johnson.*)

CANTANHEDE, Plinio, director, Economics Division, National Petroleum Council of Brazil. (*G. C. Carr; J. E. de Cunha Bahiana.*)

EKSERDJIAN, N. Martin, alternate director, I.P.C. Groups, Economic & General Secretariat Limited. (*E. C. Masterson; C. T. Barber.*)

FERRIDAY-PEARSON, James Ernest, chemical engineer, Messrs. Berry Wiggins & Co. Ltd. (*G. H. D. Holmes; M. H. Davies.*)

GIBSON, David Stuart, field chemist, Trinidad Petroleum Development Co. Ltd. (*J. C. Collcott; C. C. Wilson.*)

GILL, Arthur, Flight Lieutenant, Royal Air Force. (*C. G. Woolven; V. G. Oehl.*)

GREGORY, Robert Kenneth, technical staff officer, Military College of Science. (*J. R. H. Whiston; G. H. Gadsby.*)

HARTNELL-PARKER, Benjamin Keith, Flight Lieutenant, Royal Air Force. (*C. G. Woolven; G. Sell.*)

HARVEY, Frederick Charles, section leader, Drawing Office, Anglo-Iranian Oil Co. Ltd. (*R. E. Adlington; H. J. Stroud.*)

HIBBLE, Philip, production supervisor, Kuwait Oil Co. Ltd. (*R. M. S. Owen; J. D. Johnson.*)

HOWE, Dennis William, technical representative, Messrs. Fletcher Miller Ltd. (*E. Cunnah; R. R. MacDonald.*)

HULME, James Alexander, manager, Development Division, Trinidad Leaseholds Ltd. (*J. B. Christian; H. Macnaughton-Jones.*)

HUNTLEY, Edward, retail marketing manager, Shell-Mex & B.P. Ltd. (*H. E. Priston; A. Moon.*)

JONES, Herbert Morgan, assistant general manager, Shell-Mex Brazil Ltd. (*G. C. Carr; D. Varcoe-Cocks.*)

JOYCE, Ronald George, assistant lubrication engineer, Messrs. Alexander Duckham & Co. Ltd. (*J. S. Jackson; G. T. Joyce.*)

KAPUR, Dharan Vir, petroleum and transport officer, Central Tractor Organisation, Indian Government. (*M. P. McCarthy; G. D. Ailawadi.*)

KENDRICK, John, contracts engineer, Messrs. Foster Wheeler Ltd. (*A. S. Bridgwater; G. Sell.*)

KUMAR, Raj, district sales engineer, Messrs. Caltex (India) Ltd. (*N. G. Gullick; G. Sefton.*)

LE PAGE, James Lambridge, civil engineer, Sarawak Oilfields Ltd. (*G. F. Hazzard; J. D. Hall.*)

LLOYD, Reginald Robert, Third Officer, Leicester City Fire Brigade. (*E. Thornton; G. Sell.*)

MALCOLM, Robert Spiers, general manager, Petroleum Marketing Agencies (British Guiana) Ltd. (*J. B. Christian; J. S. Kerbey.*)

MARRIOTT, Ian Stephen, technical assistant, The Shell Caribbean Petroleum Co. Ltd. (*K. G. Tait; A. E. Johnson.*)

MELTON, Bryant, shift production operator, Kuwait Oil Co. Ltd. (*R. M. S. Owen; J. D. Johnson.*)

PARKINSON, Harry, manager, Arcoleine Lubricants (1935) Ltd. (*E. R. Wilson; T. G. Provest.*)

POCOCK, Hugh Raymond Spilsbury, general manager, Shell-Mex Brazil Ltd. (*G. C. Carr; D. Varcoe-Cocks.*)

RICHARDSON, Frank, chief inspector, Weights and Measures Dept., Nottingham. (*P. Kerr; G. Sell.*)

SAW, Walter William. branch chemist, Vacuum Oil Co. Pty. Ltd. (*M. T. Cowles; H. B. Borwick.*)

STANLEY-CARY, Edward Nicholas, management, Shell-Mex & B.P. Ltd. (*H. E. Priston; A. Moon.*)

TAYLOR, Norman William Osborne, technical assistant, Anglo-Iranian Oil Co. Ltd. (*J. W. Hyde; P. Fleming.*)

THREADGOLD, Philip, assistant physicist, Anglo-Iranian Oil Co. Ltd. (*D. Commins; R. K. Dickie.*)

TOURRET, Richard, research engineer, "Shell" Refining & Marketing Co. Ltd. (*C. D. Brewer; E. T. Hutt.*)

TRESIDDER, Charles Gerald, technical advisor, Vacuum Oil Co. Ltd. (*S. J. M. Auld; H. M. Davies.*)

TREWEEK, Joseph Leonard, general manager, Messrs. R. D. Nicol & Co. Ltd. (*A. E. Lawson; P. Kerr.*)

WHALEBONE, Edward Charles, manager, Public Works Division, Messrs. Alexander Duckham & Co. Ltd. (*A. C. Pepper*).

WHITGREAVE, Harold Johnston, technical representative, Marine and Industrial Lubricants Ltd. (*G. W. D'Arcy-Evans; G. H. Harries.*)

Transfers

BENJAMIN, Timothy Edward Ashley, sales promotion, Regent Oil Co. Ltd. (*G. Sefton; T. F. McGuiness*) (*Student to Associate Member.*)

COSSINS, Donald, inspecting engineer, National Oil Refineries Ltd. (*J. A. Cree; P. F. Ellis*) (*Student to Associate Fellow.*)

DAVIES, Howard Merrett, petroleum technologist, Vacuum Oil Co. Ltd. (*S. J. M. Auld; C. Chilvers*) (*Associate Fellow to Fellow.*)

GOODMAN, Leonard, development assistant, National Oil Refineries Ltd. (*P. F. Ellis; E. J. Horley*) (*Student to Associate Fellow.*)

STEPHENSON, Maurice, senior reservoir engineer/field superintendent, Shell Caribbean Petroleum Co. (*L. C. Stevens; W. L. Forster*) (*Associate Member to Fellow.*)

THISTLETON, Paul, chemical engineer, Esso European Laboratories Ltd. (*E. B. Evans; A. Osborn*) (*Student to Associate Fellow.*)

WATSON, Arthur Lennox, works manager, Messrs. Taylor & Son. (*W. Kay; F. Dakin*) (*Student to Associate Member.*)

NEW MEMBERS

The following elections have been made by the Council in accordance with the By-laws.

Elections are subject to confirmation in accordance with the By-laws.

As Fellow

SCHULTZ, O. R. G.

As Members

FORREST, R. LEGG, H. W. L. STEWART, H. A.

As Associate Members

BRAHAM, J. R.
BRAY, F. H.
CRUTCHLEIGH-FITZPATRICK, D. P.
EVANS, A.
HALL, A. E.
LEWIS, T. P.
NORRIS, A. C.
SMITH, A. W. G.
WILBY, P. T.

As Associate Fellows

ACTON, W. S.
BABINGTON, A. M.
BUIE, W. C.
CALDWELL, A. B.
CARPENTER, A.
DE PAIVA, G. A.
EAST, F.
GANLEY, A. W.
HARDIE, D. J.
JOHN, R. M. M.
KYNASTON, A. H.
MACDONALD, J. M.
PITTS, D. J. F.
RAE, J.
RENTON, W. C.
ROBINSON, J. H.
SAMSON, F. H.
SMALLWOOD, R. A.
THOMAS, W. I.
TRIST, M. B. F.
TURNER, K.
WATSON, T. W.
WILLIAMSON, D. L.
WOOD, J. H.

Transferred from Students to Associate Fellows

MARTIN, R. E. MOCKFORD, D. J. STOUT, K. R.

As Student

PICKARD, R. J.

Consett Iron Co. Ltd.—view of 130 ft. Breeches Piping and Skiphoist, Dust Catcher and Stoves coated with "Bitumastic" Aluminium Heat Resisting Solution.
"BITUMASTIC"
REGISTERED TRADE MARK
Anti-corrosive coatings
for
INDUSTRIAL
IRON AND STEELWORK
Industrial plant creates its own problems so far as corrosion is concerned. Airborne grit, moisture laden atmosphere, smoke and acid fumes all contribute to the corrosive conditions usually encountered.
A paint film, to be successful, must withstand these conditions and provide a full measure of protection for the underlying metal.
Specially designed coatings for industrial application have long been a feature of the Wailes Dove service. We shall be interested to have details of your particular corrosion problem. Why not write to us to-day?
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Specialists in the design and fabrication of plant for the most exacting needs of modern large scale production. Petroleum technologists will find our experienced Chemical Engineers very co-operative in securing the exact result required. May we collaborate?

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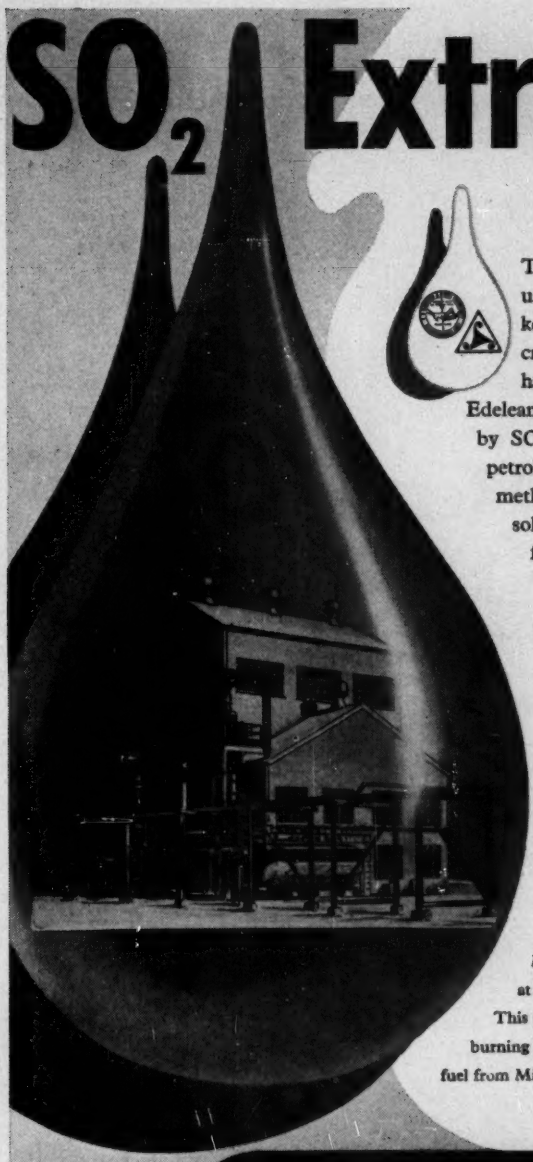
SO_2 Extraction



The Edeleanu Process has long been used for the production of high quality kerosenes from aromatic and high-sulfur crudes. For many years, Badger engineers have been expert in the utilization of the Edeleanu Process, and have applied extraction by SO_2 to the refining of a wide range of petroleum fractions. Uses include improved methods of producing pure aromatics, special solvents, transformer oils, clean burning furnace oils, and high cetane diesel fuels. With the supply trend toward crudes of more difficult refining characteristics, industry is turning more and more towards SO_2 extraction. Badger's experience in the development and application of SO_2 extraction is proven by many Badger-built SO_2 units working successfully for refineries in Europe and abroad.

An 1,800 BSD Charge Capacity SO_2 Extraction Unit recently engineered by Badger for Caltex Petroleum Maatschappij, (Nederland) N.V. at Pernis, Rotterdam, Holland. This plant produces high grade burning kerosene and turbo jet fuel from Middle Eastern crude.

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Process Engineers and Constructors for the Petroleum, Chemical and Petro-Chemical Industries

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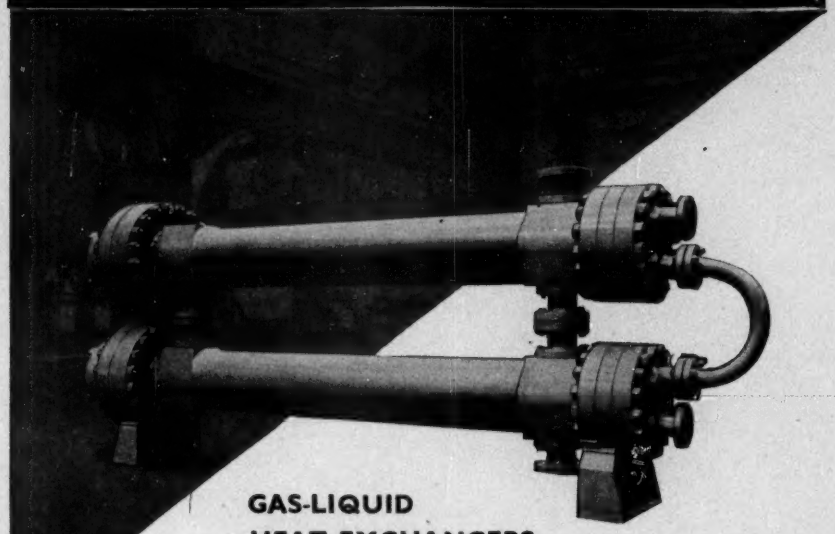

GAS-LIQUID
HEAT EXCHANGERS

Oil Pressure in Tubes	-	**1,500 lbs. per sq. in.**
Gas Pressure in Shell	-	**1,500 lbs. per sq. in.**

The Shells of these Units consist of hollow forgings, the covers for the Shell and Floating End and the Liquid Channel being of Cast Steel.

The two Units shown form part of a battery of eight similar Units supplied to the Anglo-Iranian Oil Co. Ltd., for service in the AGHA JARI Field.

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A. F. CRAIG
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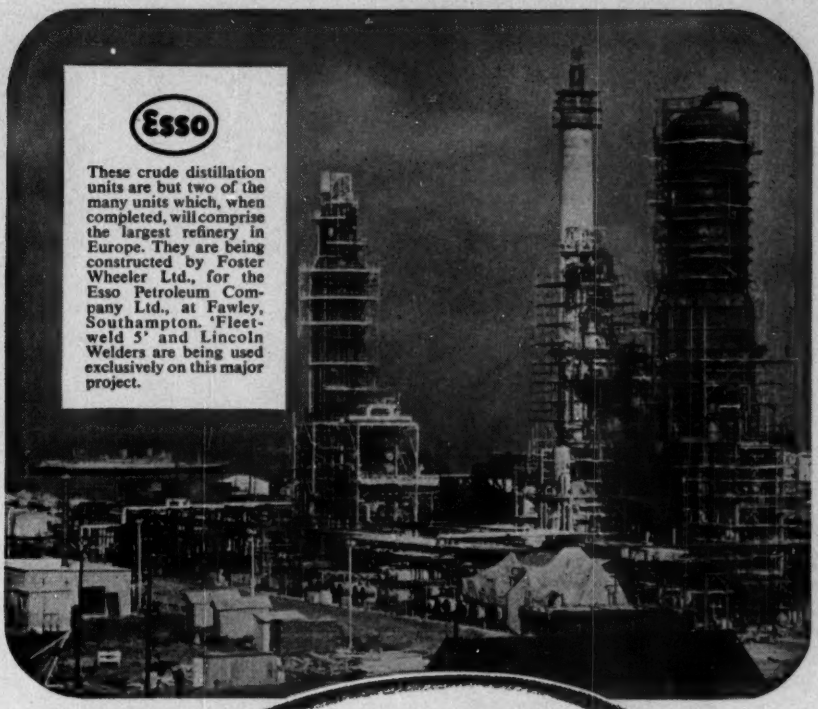
Esso
These crude distillation units are but two of the many units which, when completed, will comprise the largest refinery in Europe. They are being constructed by Foster Wheeler Ltd., for the Esso Petroleum Company Ltd., at Fawley, Southampton. 'Fleetweld 5' and Lincoln Welders are being used exclusively on this major project.

An Esso photograph by William Martin Ltd.

'We ought to ask Lincoln before we decide'

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World's largest manufacturers of arc-welding equipment and electrodes

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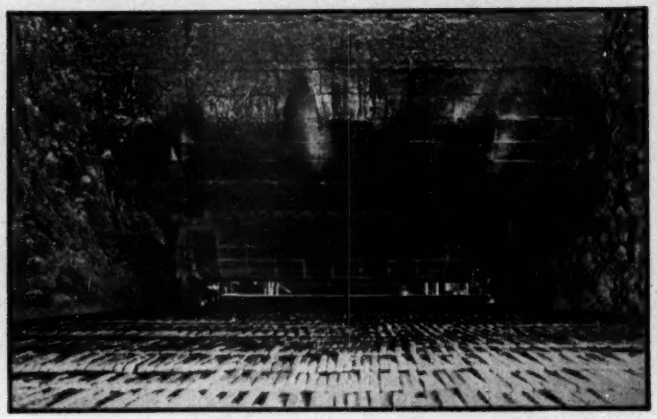

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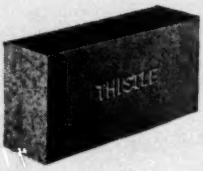
Made from selected fireclays by most modern methods under constant laboratory control "Nettle" and "Thistle" have set a standard for consistency of quality.



Full particulars of our Firebrick Brands, Refractory Cements, Castables and Concretes will be gladly sent on request.

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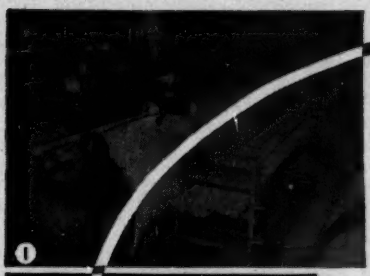
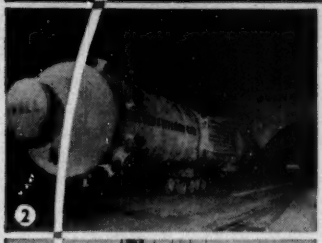
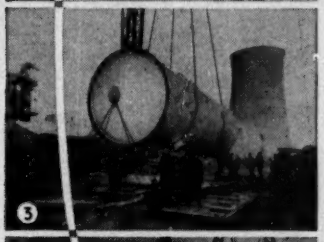
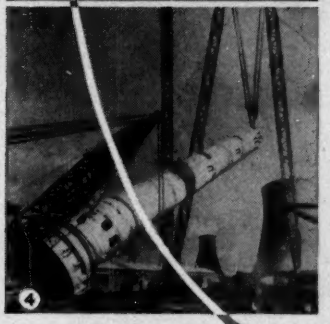








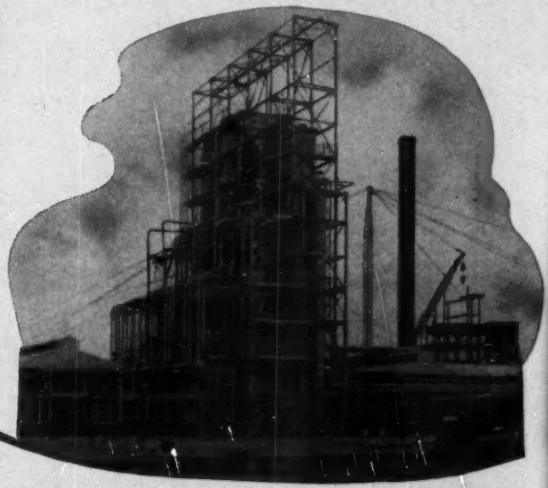
BABCOCK pressure vessels

FOR

STANLOW REFINERY

Babcock & Wilcox, Ltd. pioneered the production of fusion welded pressure vessels in 1931 and have since manufactured many hundreds of such vessels up to the largest sizes and for the highest pressures, for use in steam generation, and in the oil and chemical industries.

The Company's works at Renfrew, Scotland—largest of their kind in Europe—are comprehensively equipped for this work, in machines, personnel and experience; and the quality of their products is safeguarded and enhanced by an unrivalled research and testing organization.



1 Fabrication of a pressure vessel in the Renfrew Works of Babcock & Wilcox, Ltd. Fusion welding of a longitudinal seam.

2 One Section (81 feet long, weighing 100 tons) part of a fractionating column 148 feet high and weighing 156 tons, entering the Mersey tunnel, en route to Stanlow refinery.

3 Sections of the fractionating column being positioned prior to welding together at site by Babcock engineers.

4 Raising the completed column into its final position.

The illustrations show fabrication, transport and erection of one of a number of Babcock pressure vessels, to the order of The Lummus Co. Ltd. for the Shell Refinery at Stanlow.

BABCOCK & WILCOX LTD

BABCOCK HOUSE, FARRINGDON STREET, LONDON, E.C.4

FOSTER WHEELER

chosen by

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MAIN CONTRACTOR

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FAWLEY REFINERY

Foster Wheeler offer complete Design-Engineering-Fabrication-Erection Service throughout the world for Petroleum, Chemical Processing and Steam Plants
FW
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Hopwood

Fire-proofing in use at chemicals-from-petroleum plant. Photograph by courtesy of Petrochemicals Ltd.
KENCRETE
FIRE-PROOFING

"Kencrete" is a light-weight, highly efficient fire-proofing material for the fire protection of structural girders, vessels, etc.

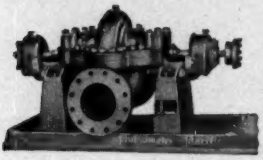
Kenyon have been called upon to undertake the heat insulation and fire protection of some of the biggest petroleum and chemical plants throughout the world. Their experience and technique in this field is invaluable, and a universal service, including technical guidance and supervision, is available at all times.

WILLIAM KENYON & SONS LIMITED DUKINFIELD CHESHIRE

KH120

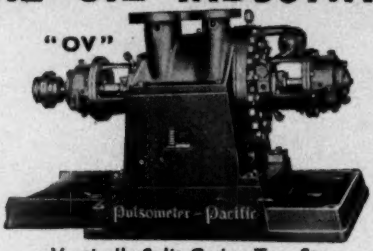
Pulsometer-Pacific

PUMPS FOR THE OIL INDUSTRY



"KH"

Horizontally Split Casing Single-Stage Hot Oil Pumps.



Vertically Split Casing Two-Stage And Three-Stage Hot Oil Pumps.

The above are some only of the Designs included.

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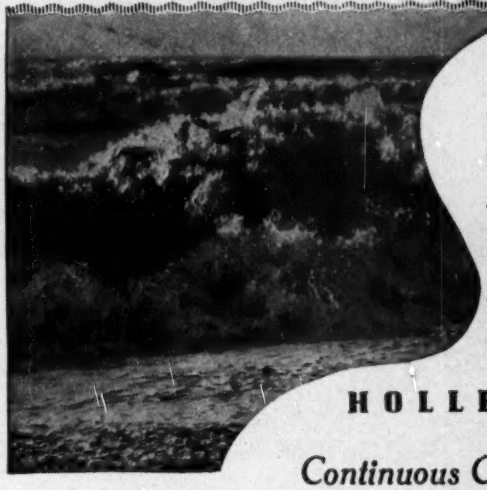

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World-Wide Licensees, **H.M. CONTINUOUS PLANT LTD.**
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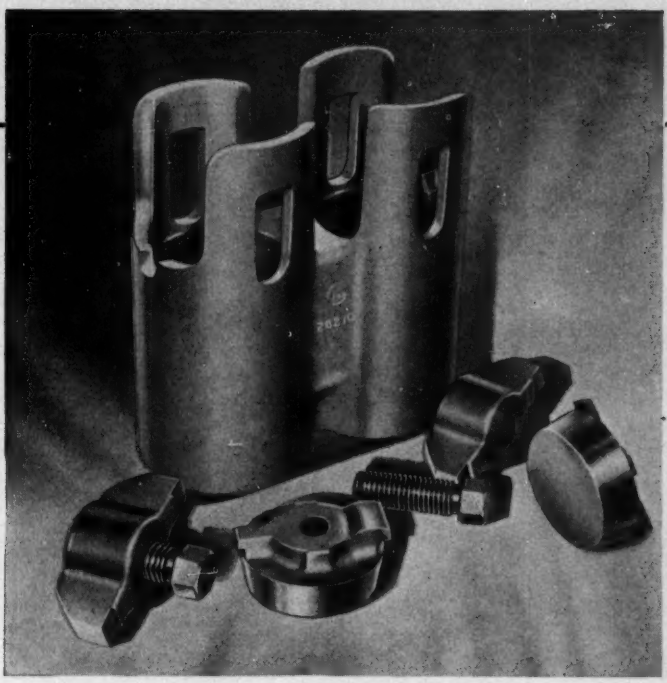

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Cast Steel Fittings

(FOR OIL REFINERY & CHEMICAL PLANTS)

for Strength & Pressure Tightness

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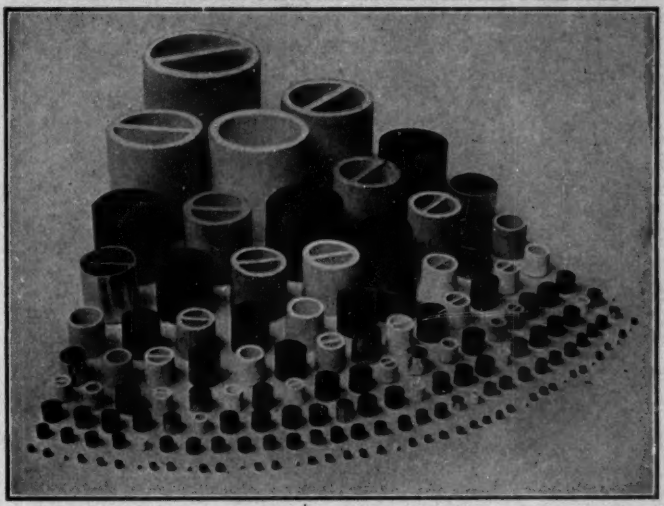

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LIQUID LEVEL
Gauges
FOR THE OIL INDUSTRY
The Klinger S. Type series, of high pressure, Liquid Level Gauges, is specially designed for modern chemical processes in oil refining and derivant producing plant, and is made in the following standard range for the indicated working pressures:
S.120 (2,000 p.s.i.) S.250 (4,000 p.s.i.)
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These are so constructed that the glass is not subjected to high mechanically applied stresses in order to make a tight joint. Tightness of the joint is provided by the internal fluid pressure, so that the glass is evenly loaded and free to adjust itself in the gauge body to inequalities of expansion.
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TO THE CATHODE

'Rusting's not what it was. Remember when, between us, we used to get through something like £900,000,000 worth of iron and steel every year?'

'And worth three times that now', said the Cathode.

'These corrosion committees', said the Anode, spitting a stream of metal ions. 'Importance of surface preparation and red lead priming. Anodic suppression . . . ! Putting ideas like that about. How are we expected to live?'

'We're not', said the Cathode. 'The latest horror is a paint that suppresses *me* as well. Modified red lead of some kind. Calcium Plumbate's the pigment. Not even sea water's going to help us when they start using that. Wish I could remember the name'.

'I give up', said the Anode. 'Science just makes life more difficult . . . What's that noise?'

'Sounds like a brush to me', said the Cathode, 'and by the speed it's coming up it must be using that new paint. Brushes out fast and covers like the devil'.

'Look out!' said the Anode.

'*This is it*', said the Cathode—**'RUSTODIAN'.**

Rustodian is made in self-colour peach, standard Light Stone and B.S.S. colours Light Brunswick Green, Dark Battleship Grey, and Imperial Brown.

*An iron surface is never perfectly uniform and in the presence of moisture a number of electric cells form on its surface. Iron dissolves from the anodes causing progressive corrosion and pitting. At the same time, in certain circumstances, (such as in the presence of sodium salts from sea water), chemical compounds forming at the cathodes tend to destroy the paint film. Rustodian suppresses electrolytic action at both anodic and cathodic areas, and therefore retards the destructive effects arising from these causes.

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ALL TYPES OF STRUCTURES

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Oil Production and Refining.

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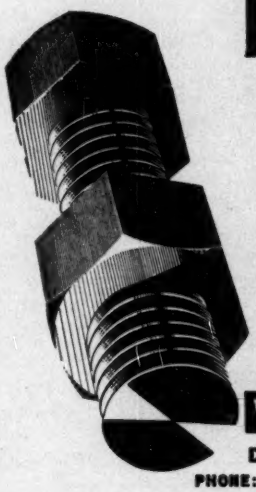
Eliminate "CREEP"
WITH
Marwin



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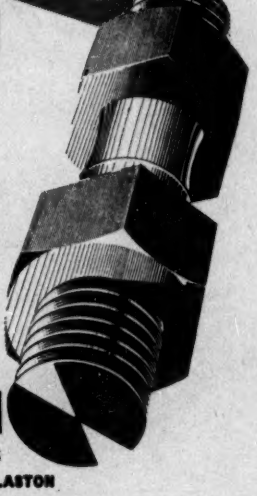
A positive defence against the effects of heat, these "Marwin" Products resist "creep" at elevated temperatures, resist embrittlement from exposures to high temperature stresses and at the same time retain high tensile strength at elevated temperatures. Write for details.



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DARLASTON S. STAFFS
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  In association with the *Chicago Bridge and Iron Co. Vapordome Roof tanks, Vaporspheres, Horton Lifter Roof tanks. (*Illustration shows tank 60 ft. dia. x 40 ft. high, with 38 ft. dia. Vapordome.*)
- **PRESSURE STORAGE SYSTEMS**
  Hemispheroids, Hortonspheroids, Spheres, Pressure Roof tanks. (*Illustration shows 20,000 bbl. capacity Hemispheroid 2½lbs. per sq. in. pressure.*)
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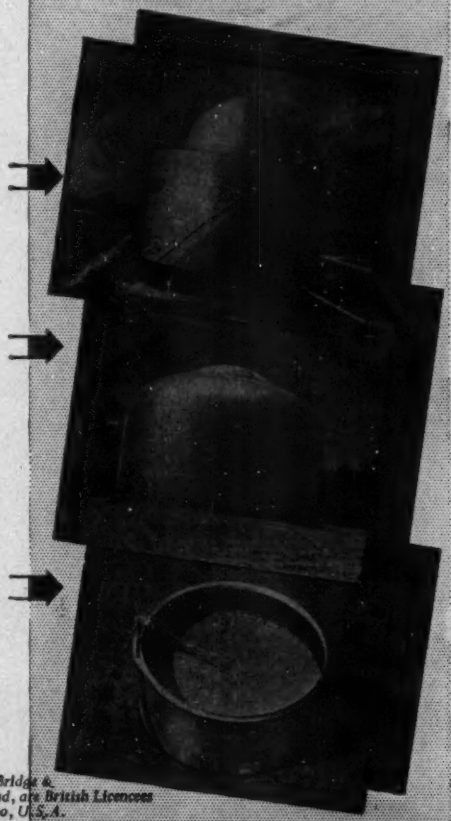

*Whessoe Limited, jointly with Motherwell Bridge & Engineering Co., Ltd., Motherwell, Scotland, are British Licencees from the Chicago Bridge & Iron Co. Chicago, U.S.A.

LONDON - 25 VICTORIA ST. S.W.1

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FOR SPEED AND STRAIGHT HOLE

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English Steel Corporation have the facilities for making any known high grade steel, and the S.A.E. Steel used in the EDECO ROCK BIT is identical with that used by the American Rock Bit makers.

All the processes from the selection of the materials through all the stages of forging, machining, welding and heat treatment are carried through inside the English Steel Corporation Plant.

There is, therefore, full assurance that the EDECO ROCK BIT is made of the finest materials and under the supervision of experts at every stage.

NEW!

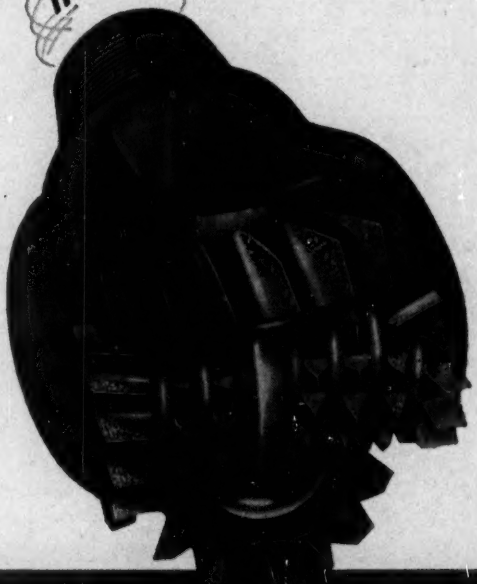
The standard range now includes:

TYPE VHW

for extremely hard and abrasive formations to overcome excessive Gauge wear.

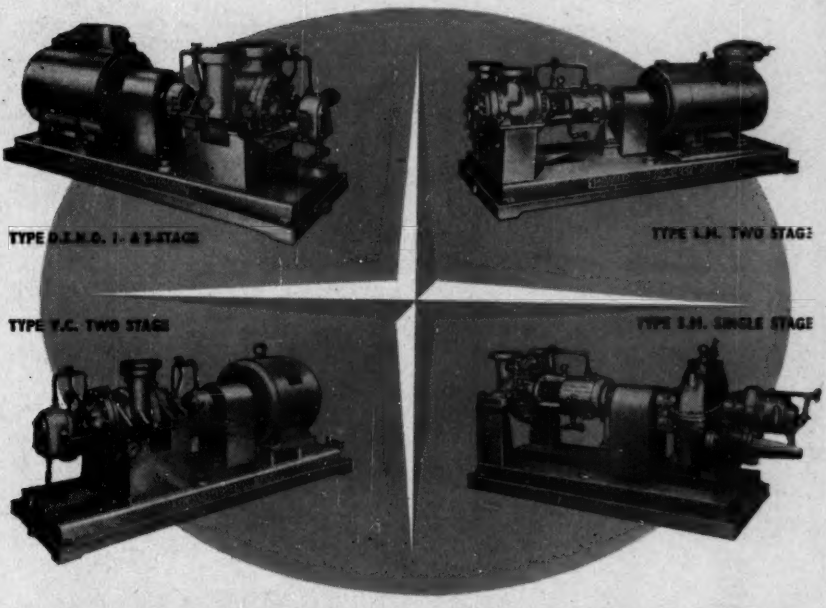
JET TYPE BITS

with special circulation nozzles for increasing the rate of penetration in soft formations.



Precision Process Pumps

FOR VARIED DUTIES



The process pumps shown above form part of the comprehensive range developed by Hayward Tyler—Byron Jackson, and illustrate by their diversity part of the aims of this combination of American "Know-how" and British craftsmanship. These aims are: (1) first class range of Process Pumps for the Oil Industry: (2) an unparalleled service to customer from receipt of enquiry to delivery: (3) reliable and reasonable delivery dates: (4) after-sales service in any part of the world. In brief — "Service with Efficiency".

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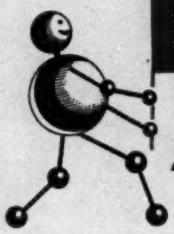
& anti-butane —



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HERMETITE

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an economical jointing specially for oil pipelines. Impervious to all hydro-carbons—it expands with heat.

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TAS/KW. 21

Unique

"Newallastic" bolts and studs have qualities which are absolutely unique. They have been tested by every known device, and have been proved to be stronger and more resistant to fatigue than bolts or studs made by the usual method.

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THE "OILWELL" No. 76 RIG

for Medium Drilling Depths of 6,000 to 10,000 ft.

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. . . with capacities far beyond most rigs of comparable size and weight.

IT'S COMPACT

. . . with unitized assemblies and oiltight, weatherproof construction throughout.

IT'S EASY TO MOVE

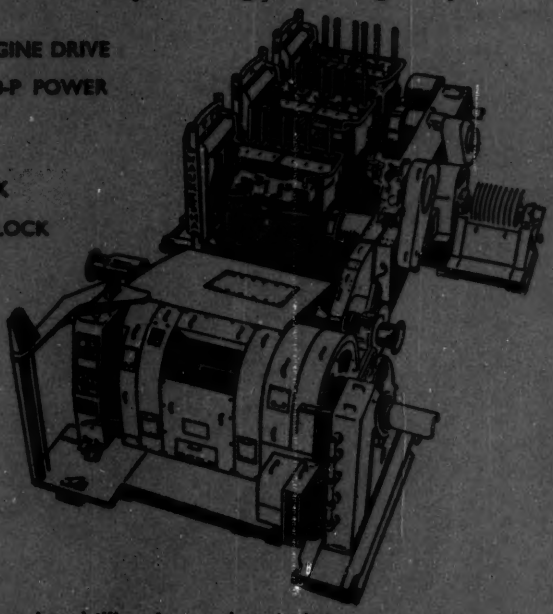
. . . either with the compound or disconnected from it.

HIGHLY FLEXIBLE COMPOUND

. . . for 2 or 3 engines with 1 or 2 pump drives, makes it suitable for a wide range of applications. Can also be furnished with hydraulic torque converters or couplings.

The following "Oilwell" Companion Equipment is Engineered for Corresponding Drilling Depths:

- No. 700 . . . 2- OR 3-ENGINE DRIVE
- No. 214-P AND No. 218-P POWER SLUSH PUMPS
- No. 56-300 SWIVEL
- No. 480 CROWN BLOCK
- No. 400 TRAVELLING BLOCK
- 20½-INCH OILBATH ROTARY
- BRANTLY HYDRAULIC FEED CONTROL WITH AUTOMATIC REGULATOR



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